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OPTIMIZING ECM TECHNIQUES AGAINST
MONOPULSE
ACQUISITION AND TRACKING RADARS

by

Kwon, Ki Hoon

September 1989

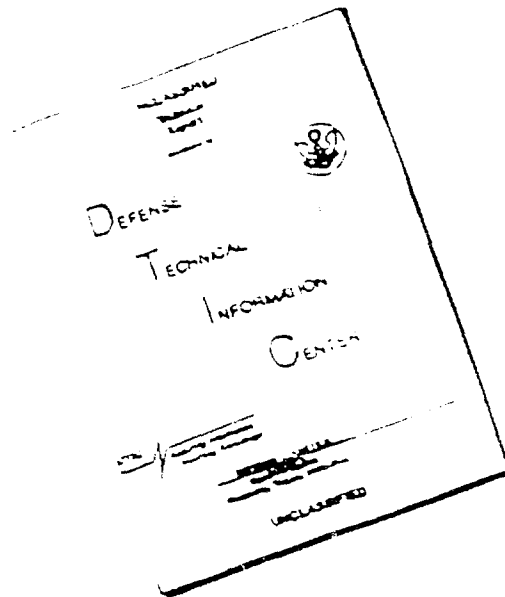
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Optimizing ECM Techniques Against Monopulse
Acquisition and Tracking Radars

by

Kwon, Ki Hoon
Major, Korean Air Force
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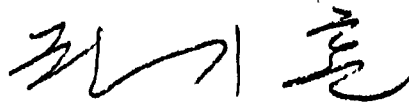
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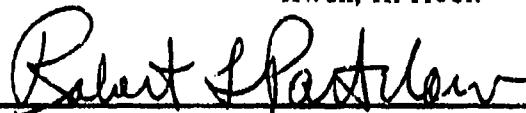
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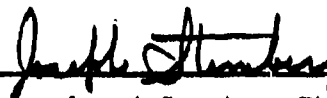
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ABSTRACT

ECM techniques against monopulse radars, which are generally employed in the Surface-to-Air Missile targeting system, are presented and analyzed. Particularly, these ECM techniques classified into five different categories, which are; denial jamming, deception jamming, passive countermeasures, decoys, and destructive countermeasures. The techniques are fully discussed. It was found difficult to quantize the jamming effectiveness of individual techniques, because ECM techniques are involved with several complex parameters and they are usually entangled together. Therefore, the methodological approach for optimizing ECM techniques is based on purely conceptual analysis of the techniques.

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LIST OF ABBREVIATIONS

AAA	Anti-Aircraft Artillery
AGC	Automatic Gain Control
ALARM	Air Launched Anti-Radiation Missile
AM	Amplitude Modulation
ARM	Anti-Radiation Missile
DECM	Deception (Deceptive) ECM
DINA	Direct Noise Amplification
ECCM	Electronic Counter Countermeasures
ECM	Electronic Countermeasures
EJ	Expendable Jammer
EW	Electronic Warfare
FM	Frequency Modulation
HARM	High-speed Anti-Radiation Missile
IF	Intermediate Frequency
INS	Inertial Navigation System
IR	Infra Red
MTI	Moving Target Indicator
PRF	Pulse Repetition Frequency
PW	Pulse Width
RADAR	Radio Detection And Ranging
RAM	Radar Absorbing Material
RAS	Radar Absorbing Structure
RCS	Radar Cross Section
RF	Radio Frequency
RGWO	Range Gate Walkoff
RPV	Remotely Piloted Vehicle
RWR	Radar Warning Receiver
SAM	Surface-to-Air Missile

SEAD	Suppression of Enemy Air Defense
SNR	Signal-to-Noise Ratio
STAR	Supersonic Tactical Anti-Radiation
TWS	Track-While-Scan
TWT	Traveling Wave Tube
UK	United Kingdom
US	United States
USSR	Union of Soviet Socialist Republics
USAF	United States Air Force
VGWO	Velocity Gate Walkoff

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I. INTRODUCTION

A. BACKGROUND

Electronic warfare (EW) has been principally concerned with techniques for seeking out enemy targets in either normal or countermeasure environments using such electronic systems as radio or radar or, for preventing the enemy from detecting friendly targets, using electronic countermeasures (ECM). Electronic counter countermeasures (ECCM) represent techniques for reducing the effectiveness of ECM. The development of these EW techniques was caused by the interaction between enemy and friendly electronic systems. This was true of the development of radar and its countermeasures which is a typical example of this interaction process.

The word radar was a code name used by the US Navy in 1940, and is an acronym derived from the phrase RADio Detection And Ranging [Ref. 1: p.1].

Before world war two, radar had been developed independently and simultaneously in several countries. During world war two, the use of radar became widespread due to the increase of air attacks by the allies and the Germans.

Since the advent of radar, air strikes have not obtained as good results. In order to thwart the operation of radar systems, both sides employed ECM devices which were made of thin aluminum foil strips. This kind of ECM technique was extremely effective in jamming the radar systems of that time. These objects became designated as "chaff" or "window" [Ref. 2: p.115 & p.252].

During the Korean war which broke out in 1950, the equipment and tactics of electronic warfare were essentially the same as those of world war two. Nevertheless, electronic warfare was indispensable by the end of 1951. According to the official united states air force (USAF) history, the aircraft and crew losses would have been triple the actual losses during the last two years of the war, without the use of electronic warfare [Ref. 3].

In the Vietnam war, surface to air missiles (SAM) and anti-aircraft artillery (AAA) greatly impacted the air campaign during the initial stages. To reduce the losses from the enemy ground threat, individual US fighters had "PODS" installed which were flexible jamming systems, adapted to the ever-changing radar threat [Ref. 2: p.253, Ref. 3: pp.2-3].

In the Yom Kippur war of October 1973, approximately 30% of the prewar Israeli aircraft were shot down by the new Egyptian SAM and AAA systems [Ref. 3: p.3, Ref. 4: pp.36-39]. This war showed that old countermeasure techniques were inadequate against the new systems.

The now familiar development pattern of radar and its countermeasures, searching for new responses to changing threats, is apparent.

In modern warfare, SAM systems which utilize acquisition and tracking radars are major threats for hampering air operations. In order to achieve the goal of air operations, it is essential to nullify the SAM batteries using proper countermeasure techniques or to destroy them. When we apply countermeasures to radar system, we need an understanding of the various types of radar systems and their principles of operations. Each type makes use of a variety of different techniques that are vulnerable to varying degrees.

The main topic of this thesis is related to monopulse radar. Monopulse radar, pioneered in the US in the late 1940s and early 1950s, to provide more precise tracking of targets for anti-aircraft missile systems, is being widely deployed by the USSR for the same function. It is intrinsically much less vulnerable than earlier conical scan type radars to deceptive type countermeasures, specifically those ECM techniques which generate spurious data on aircraft position in azimuth, elevation and range. Due to the several advantages of monopulse radars, the Soviets have been using increasing numbers of them with their anti-aircraft missile systems, both ground and ship based.

The objective of this thesis is to determine optimum ECM techniques which apply against the monopulse acquisition and tracking radars that are used for SAM targeting.

B. COMPARISON OF SEQUENTIAL AND MONOPULSE RADARS

According to angle tracking method, tracking radars fall into two distinct categories. They are the continuous tracking radar and the track-while-scan (TWS) radar. The first provides continuous tracking data on a single target, the second, TWS radar, provides near simultaneous tracking data on multiple targets.

In continuous tracking radar, the antenna is pointed at the selected target by a servomechanism actuated by an error signal. Several techniques are used for the detection of target angular errors.

One method of obtaining the direction and the magnitude of the angular error is lobe switching, also called sequential switching or sequential lobing, which is done by alternatively changing the antenna beam between two positions. This method generates two overlapping beams which have a small angular separation in one coordinate as shown in Figure 1 [Ref. 5: pp.153-154].

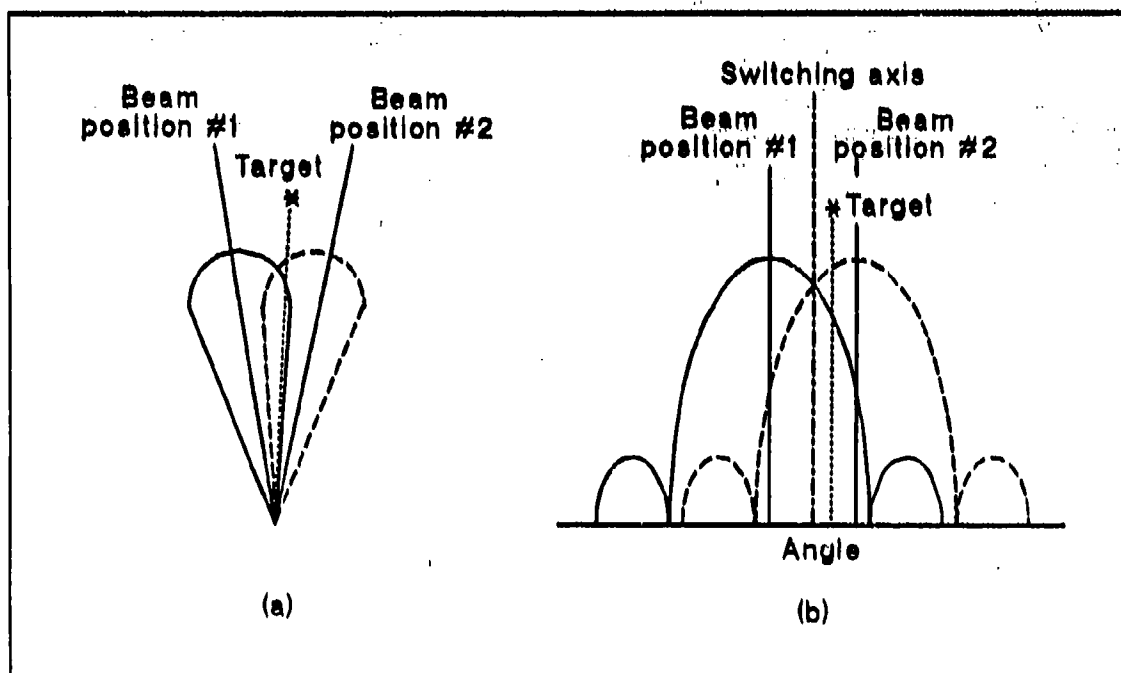


Figure 1. Lobe switching antenna patterns in one dimension. (a) Polar form.(b) Rectangular form.

In order for lobe switching to complete angle tracking in elevation and azimuth, it requires a minimum of four successive beam positions as shown in Figure 2 (a). This is also true in monopulse, but it is not successive beams but simultaneous beams.

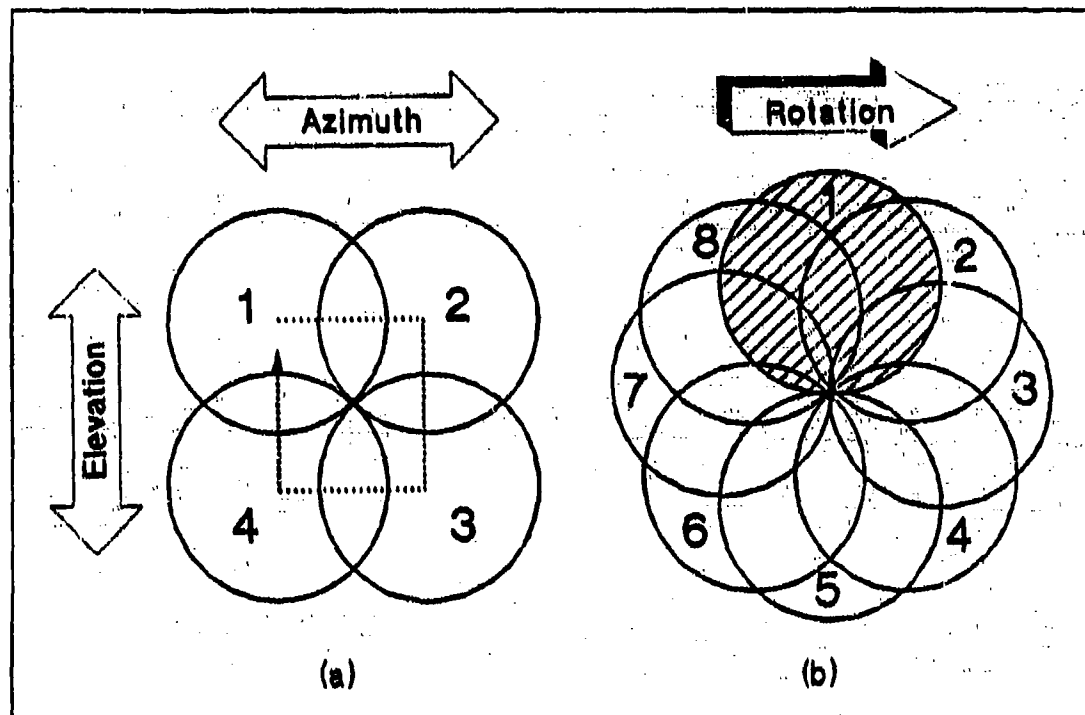


Figure 2. Two categories of sequential lobing. (a) Lobe switching beam pattern in two dimension. (b) Conical scan with 8 beams per scan.

Another method is conical scanning. It is a logical extension of the lobe switching technique. The beam rotates continuously in a circular path, centered around the crossover axis, rather than stepwise motion of the beam between four discrete positions. Even though the beam motion is continuous in conical scan, the receiving target echo will be displayed only when each transmitted pulse reaches the target. For example, if the scanning rate is forty times per second, and the pulse repetition frequency is 320 pulse per second, there are eight beam positions per scan as shown in Figure 2 (b). The above two methods, lobe switching and conical scan, are included in the general term, sequential lobing [Ref. 6: p.5].

A principal source of error in these methods is the fluctuation of echo signal caused by fluctuating target cross section. Pulse-to-pulse amplitude fluctuations of the echo signal can degrade the accuracy of the tracking radars which need many pulses to generate the error signal.

Another disadvantage of sequential lobing is the limitation on the data rate with its required four minimum successive echo pulses for the complete angle tracking in azimuth and elevation. This can be a serious limitation in target tracking of large angular accelerations. There is the further disadvantage that mechanical vibration makes it hard to maintain accurate boresight alignment in conical scan radars.

In order to eliminate these and other problems, monopulse techniques were developed. Monopulse has several advantages comparing with lobe switching and conical scan techniques [Ref. 6; pp.6-7].

Monopulse operation is similar in concept to lobe switching, but instead of comparing the target echoes obtained from sequential beam positions, it receives several target echoes simultaneously and then makes the comparisons on the basis of a single pulse. Therefore monopulse can provide a higher data rate than the other techniques because angle information is available from every received pulse.

Theoretically, monopulse radars are free of errors due to pulse-to-pulse fluctuations in target echo intensity because the fluctuations have no effect on the ratio of signals received simultaneously from opposing lobes during each pulse.

Assuming that the other radar parameters are the same, the Signal-to-Noise Ratio (SNR) is higher in monopulse since the sum beam is pointed at the target both in transmission and reception. This results in better detection capability and less tracking error due to thermal noise.

Monopulse has better stability of the boresight axis because this technique does not use the mechanical vibration of the feed or reflector.

In sequential lobing techniques, scanning information is disclosed easily to an unfriendly observer. It makes the radar vulnerable to some countermeasures which utilize that information. However, monopulse transmission has no scan during tracking.

In conical scan, the scan rate has an effect on tracking range. This is because the beam direction between transmission and reception must be the same within certain limits. Monopulse is free of this restriction. The pulse repetition frequency (PRF) is the only factor limiting the maximum unambiguous range in monopulse.

The disadvantages of monopulse over the other techniques are complexity and high cost. Monopulse requires multiple receivers, while the other techniques need only one. In addition, monopulse receivers must be well designed and matched to track one another in gain and phase.

C. OVERVIEW

This thesis is composed of five chapters. Chapter one describes the differences between sequential lobing and simultaneous lobing or monopulse tracking methods. Chapter two describes the basic principles of monopulse radars, especially two distinctive categories; amplitude-comparison monopulse and phase-comparison monopulse. Chapter three contains various ECM techniques against monopulse radars in accordance with the five different categories. They are: denial jamming, deception jamming, passive jamming, decoys, and destructive methods. Chapter four analyzes these ECM techniques conceptually. Finally, chapter five arrives at the conclusions regarding the employment of the various techniques.

II. MONOPULSE TRACKING RADAR SYSTEMS

A. MONOPULSE CONCEPT

Sequential-lobing techniques, including conical scan used earlier for target tracking, are found to be degraded in angle tracking accuracy by the effects of target scintillation. To eliminate this source of error, the technique for finding precise direction by comparing the return echo on two or more antenna lobes simultaneously was developed. Sequential-lobing tracking radar including conical scan require a minimum of four pulses in order to extract the angle error signal. Monopulse tracking radar, however, needs just one pulse.

Pulse-to-pulse amplitude fluctuations of the echo signal have no effect on tracking accuracy if the angular measurement is made on the basis of one pulse rather than many. There are several methods by which angle error data might be obtained with only a single pulse. More than one antenna beam is used simultaneously in these methods, compared with the lobe-switching or conical scan tracker which use one antenna beam on a time-shared basis. The angle direction of the echo signal can be determined in a single pulse system by measuring the relative phase or the relative amplitude of the echo signal received in each beam. The names simultaneous lobing and monopulse are used to describe those tracking techniques which extract angle error information on the basis of a single pulse.

B. TWO DISTINCTIVE CATEGORIES

1. Amplitude-Comparison Monopulse Radar

The basic amplitude-comparison monopulse [Ref. 5: pp.160-164] utilizes two overlapping antenna beams to obtain an angle error signal. The radar senses the target displacement by comparing the amplitude of the received echo signals. These two beams may be generated with a reflector or a lens antenna illuminated by two adjacent feeds. The basic amplitude-comparison monopulse system is

shown in Figure 3. Figure 3 (a) shows the overlapping antenna patterns. If the target is deviated by an angle from the equisignal boresight axis the signal received from that side of the beam pattern has a greater amplitude than that from the other side. Figure 3 (b) shows the sum pattern and Figure 3 (c) shows the difference pattern. The sum pattern is used for target amplitude detection and as a reference signal, while the difference patterns are used for angle discrimination. Signals received from the sum and the difference patterns are amplified separately and combined in a phase detector to produce the error signal characteristic shown in Figure 3 (d).

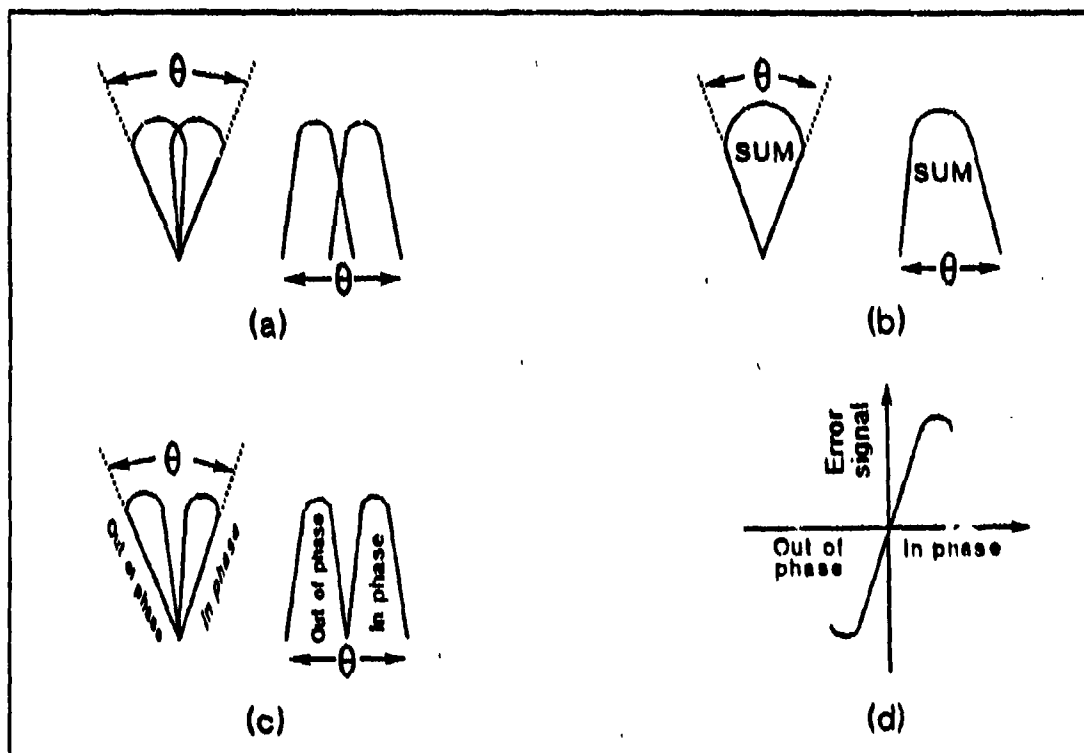


Figure 3. Monopulse antenna patterns (Polar and Rectangular form) and error signal.

Amplitude-comparison monopulse radars may be implemented in either one or both angular coordinates. Figure 4 shows a block diagram of the amplitude-comparison monopulse radar for a single angular coordinate. The

two adjacent antenna feeds are usually connected with electromagnetic field comparison circuits such as a hybrid junction or a "magic T". It has only two channels. The transmission line connected to the sum channel provides range and phase reference information. The angle error signal is generated by phase detector. The sign of the difference pattern points out the detected targets direction relative to boresight (left/right), (up/down).

For example, in the case of azimuth, plus sign could mean right-side and minus sign left-side. In case of the elevation, opposite signs mean up or down. If the target is located on boresight, the difference pattern produces zero magnitude of angular error. The plus and minus signs actually mean in-phase and 180° out-phase, relative to the sum or reference channel. The magnitude of angle error signal is proportional to the angular error and the sign of angular error is proportional to the targets direction relative to boresight. These angular error signals control an antenna servo mechanism to perform automatic target tracking in angular coordinates.

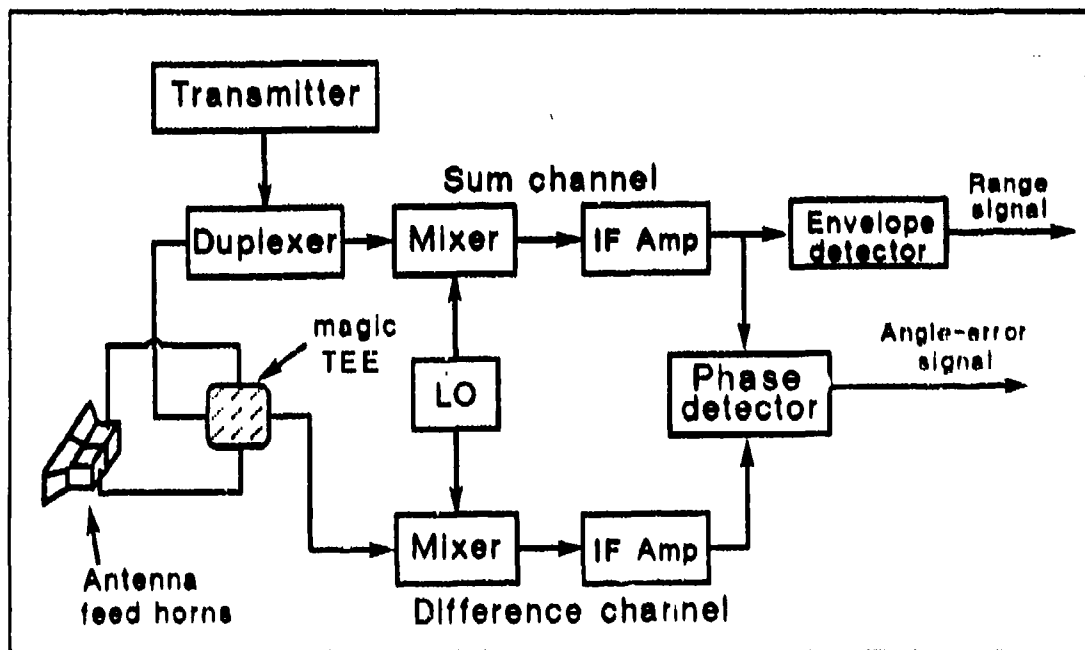


Figure 4. Block diagram of amplitude-comparison monopulse radar (one angular coordinate).

Even though phase comparison is intrinsically a part of amplitude-comparison monopulse radar, the angular error signal is basically derived by comparing the echo amplitudes from simultaneous offset beams. The phase relationship between the signals in the offset beams is not used. The purpose of the phase detector is to conveniently provide the sign of the error signal.

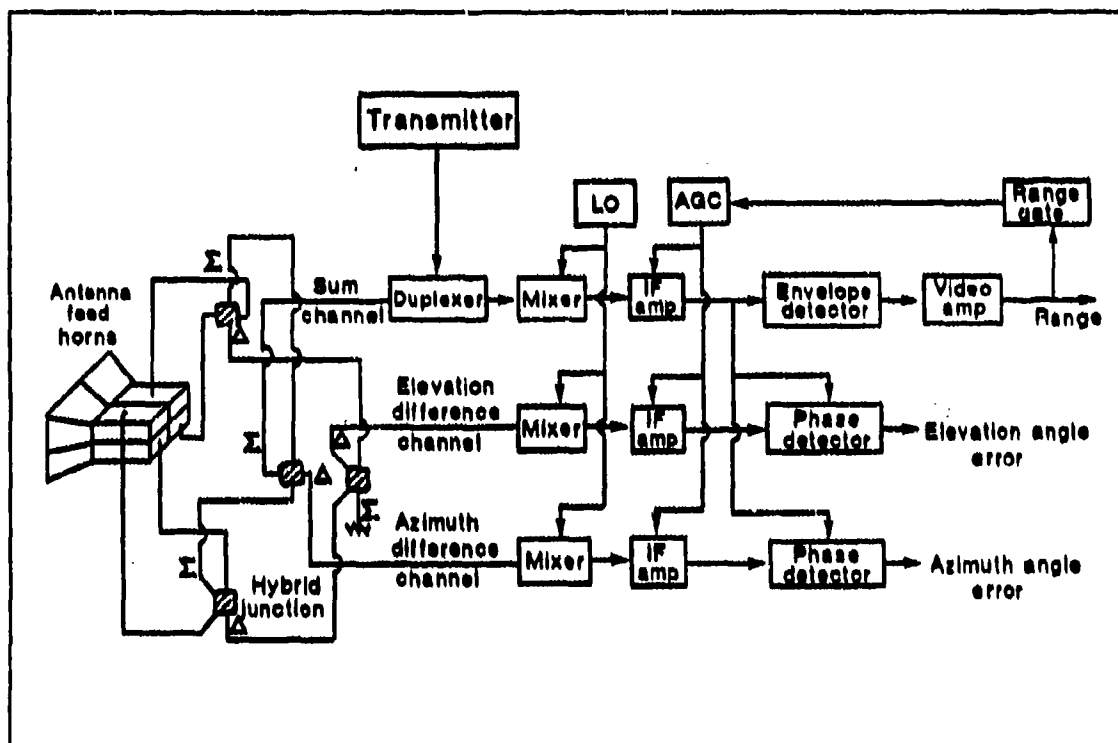


Figure 5. Block diagram of two-coordinate (azimuth and elevation) amplitude-comparison monopulse tracking radar.

Figure 5 shows a block diagram of an amplitude-comparison monopulse radar with both elevation and azimuth error signals. The cluster of four feeds makes four partially overlapping antenna beams. The feeds might be utilized with a parabolic reflector, Cassegrain antenna, or a lens. The sum pattern is formed by all four feeds. The difference pattern in one plane is formed by taking the sum of two adjacent feeds and subtracting this from the sum of the other two adjacent feeds. The difference pattern in the orthogonal plane is obtained by combining the differences of the orthogonal adjacent pairs. Four hybrid junctions generate

three channels which are the sum channel, elevation difference channel and azimuth difference channel. Three separate mixers and IF amplifiers are installed, one for each channel. All three mixers operate from a single local oscillator in order to maintain the phase relationships between the three channels. Two phase detectors extract the angle error information, one for azimuth, the other for elevation. Range information is extracted from the output of the sum channel after envelope detection.

The monopulse antenna must generate a sum pattern with high efficiency and a difference pattern with a large value of slope at the crossover of the offset beams. The greater the SNR and the steeper the slope of the error signal in the vicinity of zero angular error, the more accuracy in the measurement of angle. Moreover, the sidelobes of both the sum and difference patterns must be low. The antenna must be capable of the desired bandwidth, and the patterns must have the desired polarization characteristics. It is difficult to fully achieve all these properties simultaneously. Thus antenna design is an important part of good monopulse radar operation.

Automatic gain control (AGC) is required in order to keep a stable closed-loop servo system for angle tracking. The AGC in a monopulse radar is accomplished by employing a voltage proportional to the sum channel IF-amplifiers output in order to control the gain of all three receiver channels. The AGC results in a constant angle sensitivity regardless of target size and range.

2. Phase-Comparison Monopulse Radar

In this technique target angle is sensed by comparing the phase of the signals received by two separate antennas. Phase-comparison monopulse [Ref. 5: pp.165-167] is similar in many ways to amplitude-comparison monopulse. However, unlike the antennas of amplitude-comparison trackers, those used in phase-comparison systems are not offset from the axis. The individual boresight axis of the antennas are parallel.

Therefore, if the target is on the antenna boresight axis, there is no phase shift, namely, in phase. If the target moves off the antenna boresight axis, there exists phase difference which points out the angular error.

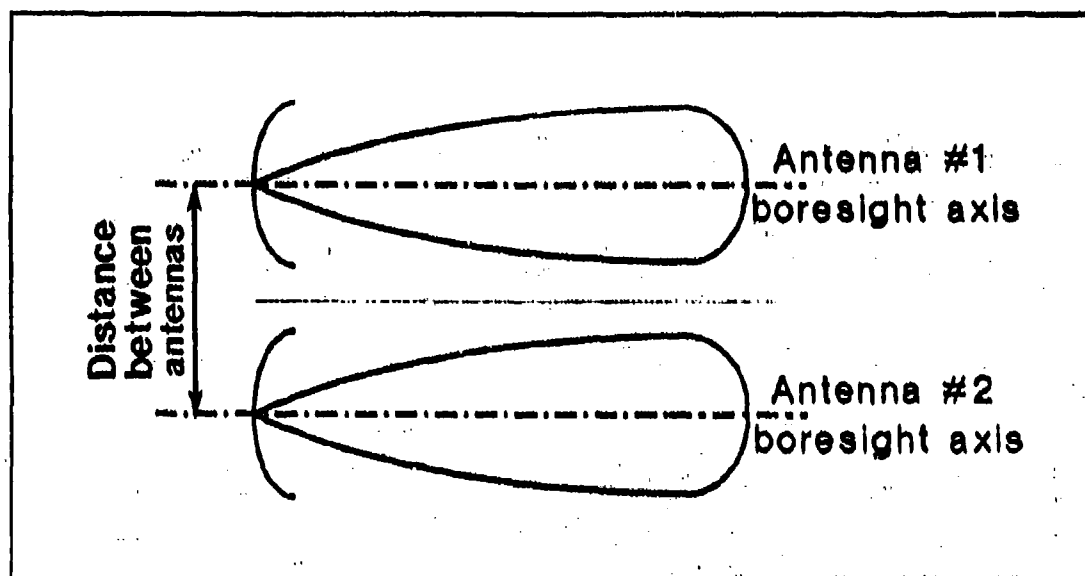


Figure 6. Antenna beam radiation patterns in phase-comparison monopulse radar.

Figure 6 shows the antenna radiation pattern for a phase-comparison monopulse radar. Because the antennas radiate separate parallel beams, the amplitude of the target echo signals coming from far field targets are very nearly the same value, but the phases are not the same depending on the relative distances from the target to each of the respective antennas, i.e., path length or phase length differences. This situation is illustrated in Figure 7.

The line of sight to the target makes an angle θ to the equisignal direction, as shown in Figure 7. R_1 representing the distance to the target from antenna 1, is :

$$R_1 = R - \frac{d}{2} \sin \theta \quad (2.1)$$

and the distance to the target from antenna 2 is:

$$R_2 = R + \frac{d}{2} \sin \theta \quad (2.2)$$

The difference between these offsets is :

$$\Delta R = R_2 - R_1 = d \sin \theta \quad (2.3)$$

This can be used to determine the phase difference :

$$\Delta \phi = \frac{2\pi \Delta R}{\lambda} = \frac{2\pi}{\lambda} d \sin \theta \quad (2.4)$$

where λ is the wavelength, and d is distance between two antenna feed horns.

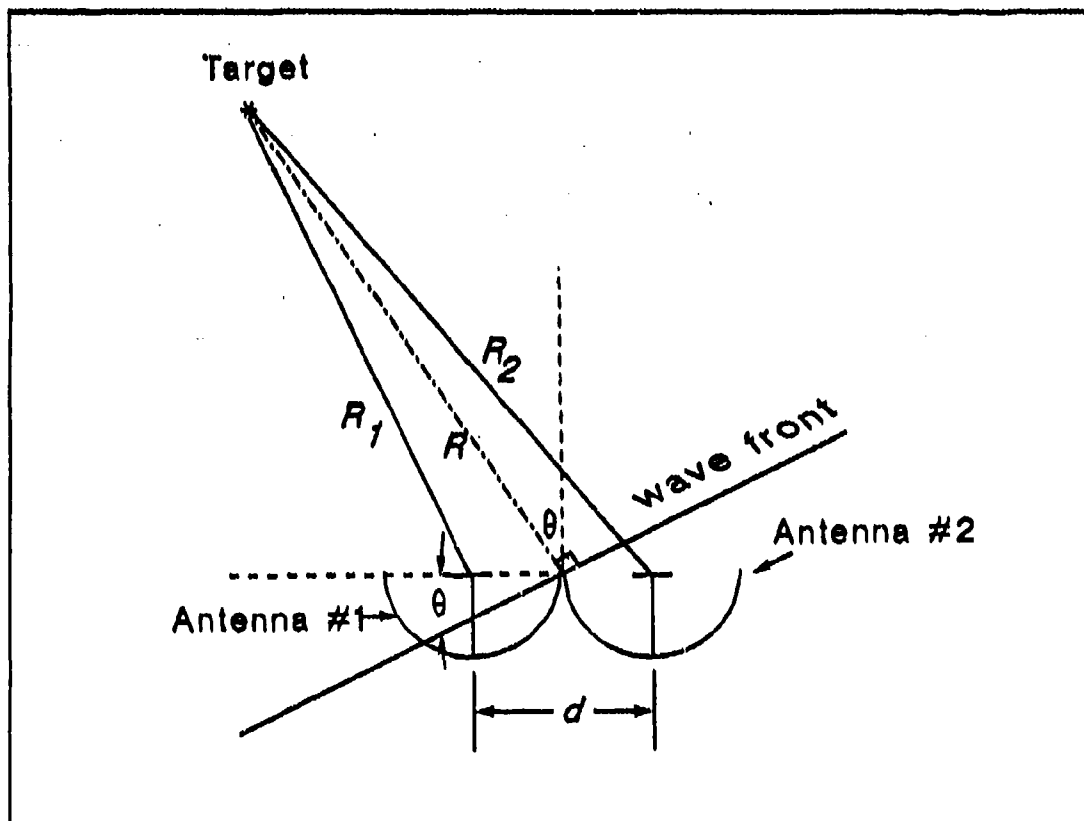


Figure 7. Wavefront phase relationships in phase comparison monopulse radar.

For small angles where $\sin \theta \approx \theta$, the phase difference between the echo signals in the two antennas is :

$$\Delta\phi \approx \frac{2\pi}{\lambda} d \theta \quad (2.5)$$

There exists a linear relationship between phase difference and angular error. It may be used to position the antennas via a servo-control loop.

In the phase-comparison principle, as applied to missile guidance, the phase difference between the signals in two fixed antennas is measured with a servo-controlled phase shifter located in one of the arms. The servo loop adjusts the phase shifter until the difference in phase between the two channels is a null. The amount of phase shift which has to be generated to make a null signal is a measure of the angular error.

Both the amplitude-comparison monopulse and the phase-comparison monopulse trackers use two antenna beams for one coordinate tracking. The measurements carried out by the two systems are different from each other. Therefore the characteristics of the antenna beams will be different, also. In the amplitude-comparison monopulse the two beams point in slightly different directions because the antenna difference patterns are offset from the antenna boresight line. This type of pattern can be generated by using one reflector with two feed horns side by side. For two coordinate tracking, it will require at least four feed horns. Any difference in the amplitudes between the two antenna outputs in the amplitude-comparison system is a result of differences in amplitude and not phase. In contrast with this the phase-comparison monopulse measures phase differences only and is not concerned with amplitude difference.

Even though tracking radars based on the phase-comparison monopulse principle have been employed, this has not been widely used compared with other angle-tracking techniques. The disadvantage of phase-comparison monopulse is that the sum signal has higher sidelobes due to the separation of the two antennas. However, this problem can be reduced by overlapping the antenna apertures.

III. ECM TECHNIQUES AGAINST MONOPULSE RADARS

A. DENIAL JAMMING

Denial jamming is defined as the technique that effects a victim radar receiver so that its effective use is denied [Ref. 7: p.55]. This terminology is also used to illustrate noise jamming, which consists of transmitting a noiselike signal in the victim's radar receiver bandwidth.

Maximum jamming power output depends on the ratings of available devices, power supply limitation, power limitations of waveguides, antenna, and other components, etc. For the jammer to get the maximum power per unit bandwidth, the bandwidth should be made as narrow as possible and the frequency spectrum matched to the victim radar receiver. In the most cases, the denial jamming bandwidth should be greater than the victim receiver bandwidth to allow for frequency set-on tolerances, drift of jammer or receiver, or to jam several radar receivers simultaneously.

Denial jamming is also called noise jamming. The objective of noise jamming is to obscure the true target echo by inserting the jammer noise signal into the victim radar receiver. Noise jamming is generated by AM or FM modulating an RF carrier wave with noise, and transmitting the result at the victim radar's frequency. The radar receiver detects relatively weak return signals from the target, therefore radar receivers must have very high sensitivity. This sensitivity causes the radar to be vulnerable to noise jamming because the jamming signal is usually of far greater amplitude than a returning echo signal from a target. The radar system can detect its target in a back ground of ambient noise. However, the SNR must be much greater than one in order to reliably detect the target. If SNR is one or less, due to the effects of noise jamming, the radar will not be able to evaluate the skin return from the target.

Denial jamming is often classified according to the emission bandwidth of the jammer. The following techniques can be applied to the monopulse acquisition and tracking radar jamming.

1. Swept Spot Jamming

Swept spot jamming is a kind of denial jamming where jamming frequency is swept across the band. Spot jamming is capable of concentrating jamming power against one particular fixed radar frequency, but it cannot jam as efficiently an entire radar frequency band. Nowadays, many radars use frequency agile techniques to counter against spot noise jamming.

In order to jam radar systems with both high power density and over a wide frequency band, swept spot jamming is nevertheless employed. Swept spot jamming tunes the high power jamming signal across a wide frequency band with sweep rates corresponding to the victim radars if frequency. Thereby all predetermined victim radars over the desired frequency band including frequency agile radars are affected by the jamming signal, as shown in Figure 8. The bandwidth of swept spot jamming thus a little bigger than the victim radar bandwidth. This results in maximum noise quality [Ref. 8: pp.273-277].

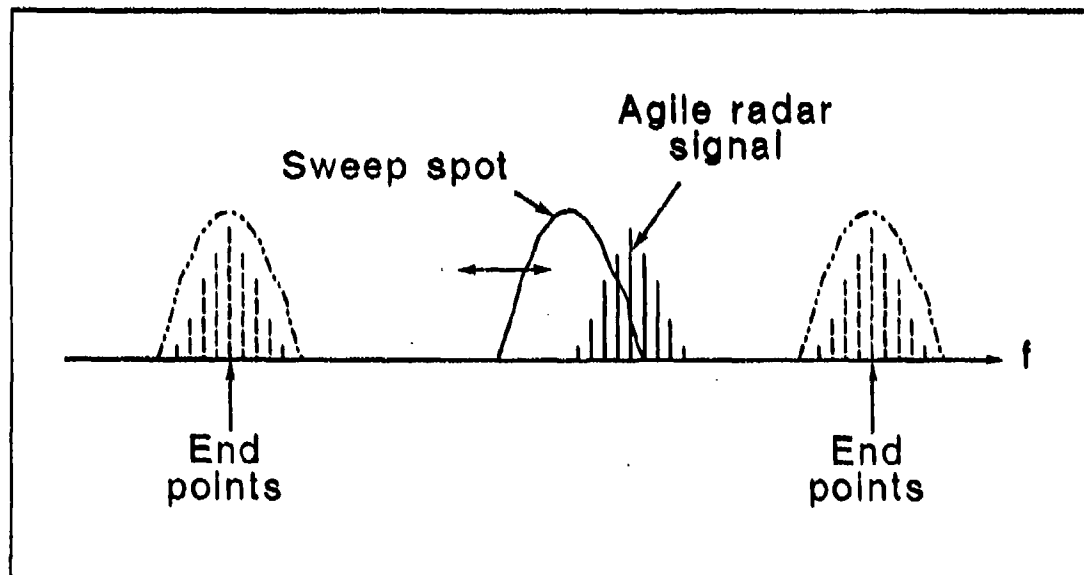


Figure 8. Swept spot jamming.

2. Barrage Jamming

Barrage jamming comprises the spreading of noise-like jamming energy over a wide frequency band, such that many victim radars or a single broadband radar can be jammed over a whole radar band simultaneously.

Barrage jamming with wide band noise-like jamming power may be generated in many ways. For example, various types of modulated electromagnetic waves can be used for the low-power sources, like semiconductor RF oscillators. For high-power source devices like the traveling wave tube (TWT) are used. Direct noise amplification (DINA) is produced by passing band-limited Gaussian noise from a low-power source through a high-power amplifier.

There are several variations of barrage jamming depending on the jamming circuitry. Figure 9 shows basic barrage jamming.

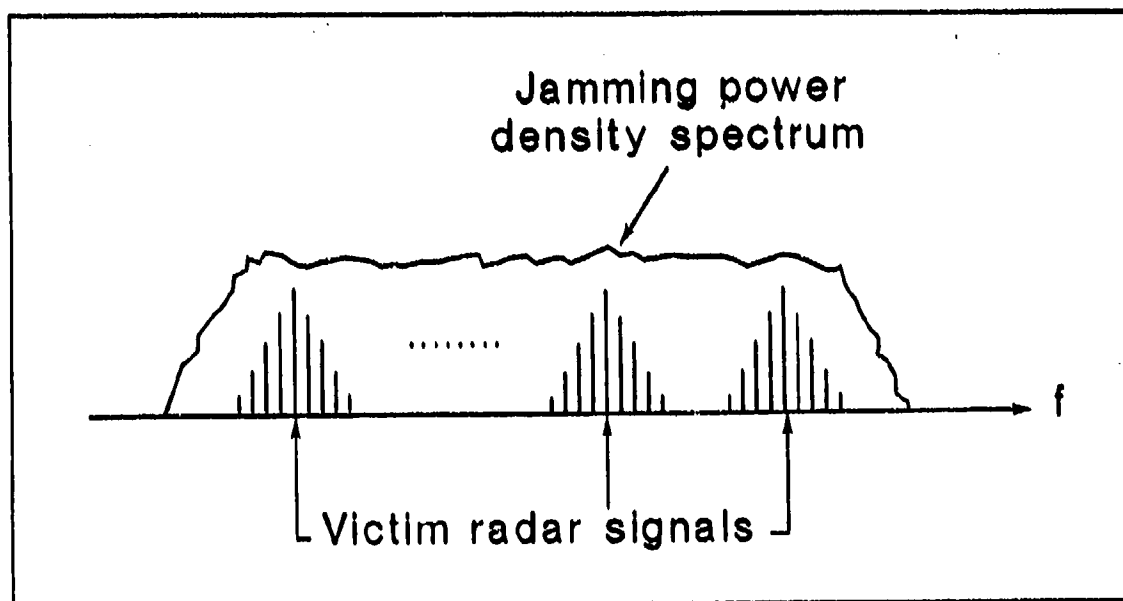


Figure 9. Barrage jamming.

3. Blinking

Blinking jamming utilizes noise jamming whose spectrum covers the bandpass of the victim radar and the jamming signal alternately turns on and off at approximately a 50% duty cycle [Ref. 7: p.481]. Blinking jamming waveforms are shown in Figure 10.

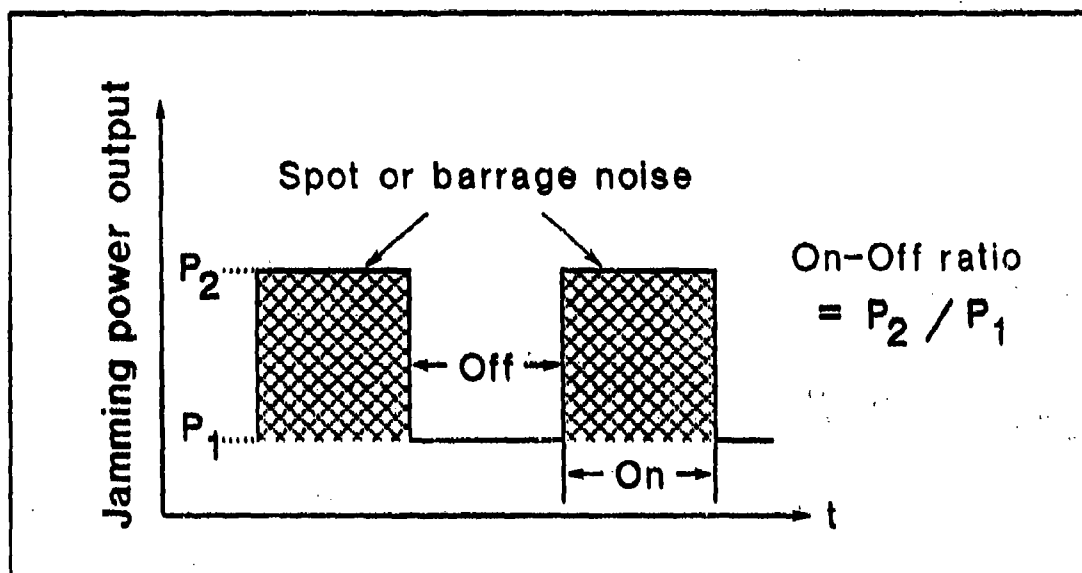


Figure 10. Blinking jamming waveforms.

In order to effectively jam a track-on-jam radar receiver, jammer on time should just exceed the time it takes the radar to go into its track-on-jam mode. The jammer off time should be just less than the time that it takes the radar to reacquire the target. Good blinking jamming maintains the radar either searching for the target or in the process of going into track-on-jam mode. Typical blink rates are in the low audio frequency range.

For blinking to be most effective, two or more synchronized blinking jammers, which are angularly separated, are required. In the case of aircraft, they can be installed on two individual aircraft. These jammers are located within the radar antennas beam but at slightly different angles. The jammers are alternately turned on and off so that the victim radar receives the strong noise signal from alternate angles around a mid point. The antenna of a single target-tracking radar will attempt to shift its tracking direction as the jammers are turned on and off, provided that the noise jamming is of sufficient strength. Depending on the interaircraft control link, this technique can be classified by five different classes, as shown in Figure 11.

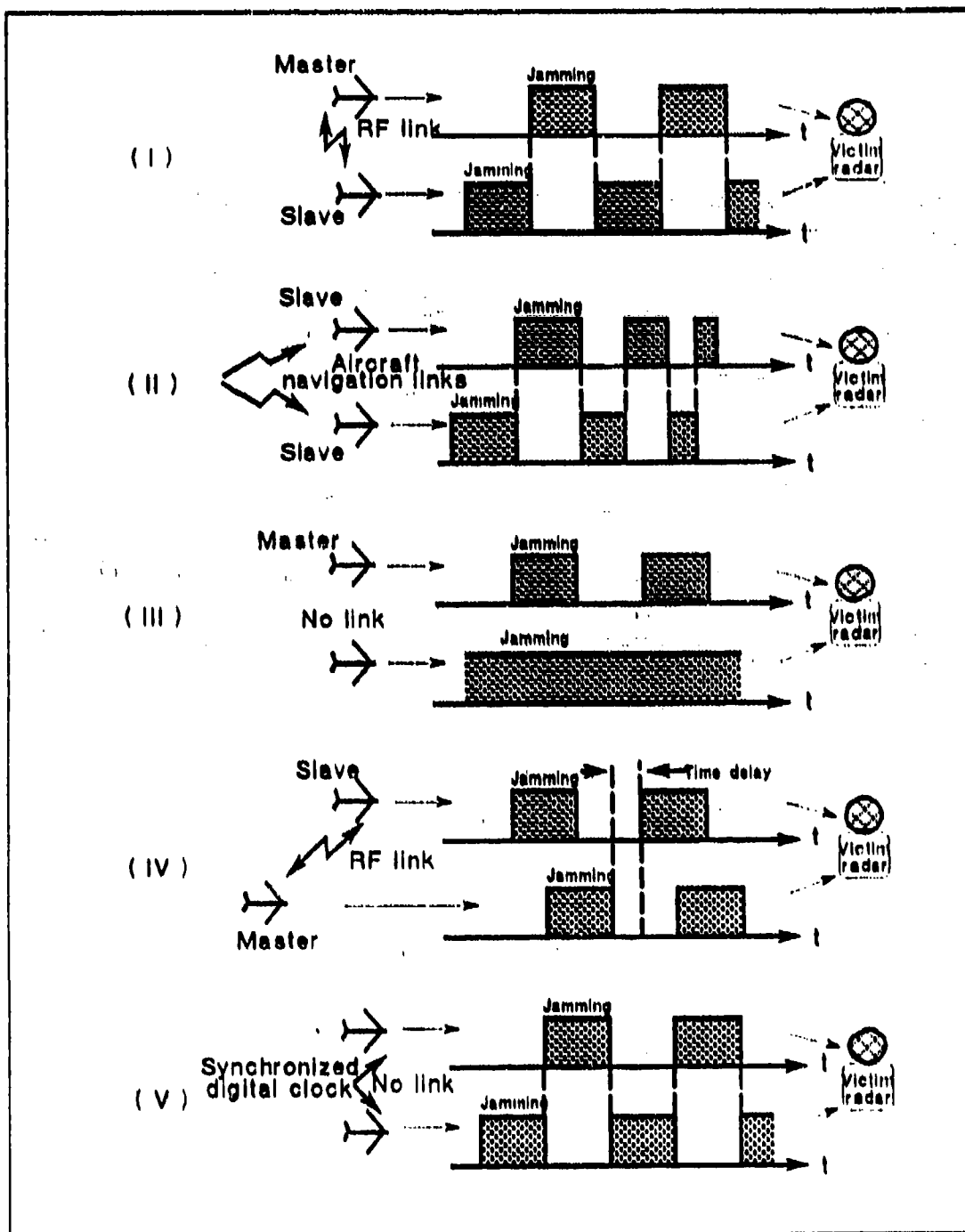


Figure 11. Blinking, synchronized multiaircraft.

When blinking is working properly, the victim radar will track from one jamming source to another in turn. This may cause the radar tracker to break-lock. Otherwise the radar tracker will have erroneous target information. Thus the control of a missile is more difficult and a missile guided by the tracking radar will miss the target due to the inaccurate target angle position information. For the maximum miss distance, the blinking rate must be considered. If the blinking rate is too high, the tracker will attenuate the jam signal. If it is too low, the missile will be able to home in on one jammer by determining precisely the angular position of individual aircraft. Optimum blinking rates are from one half to ten Hertz [Ref. 9: p.3d-21].

B. DECEPTION JAMMING

Denial jamming can deny range information, but it may not deny azimuth and elevation information to a fire control radar if several denial jammers are not employed at different locations simultaneously. Thus a missile may hit a target which has a denial jammer for own self-protection.

However, deception jamming provides a little different method against fire control and missile guidance radars in order to decrease the aircraft kill probability by the missile. The objective of deception jamming is to confuse or deceive the true target echo by inserting properly altered replicas of the true target echo into the victim radar systems. This technique will make it impossible to get the correct information by providing many realistic false targets on the display. Deception jamming may be able to degrade the accuracy of tracking information not only in range and velocity, but also in azimuth and elevation. If angle jamming related to azimuth and elevation is implemented successfully, in general, it can cause the victim tracking radar to break lock.

The basic form of deception jamming is repeater jamming. Its implementation is to reradiate modified replicas of the received victim radar signal correlating with time delay. The conspicuous characteristics of repeater jamming is to coherently store the victim radar signal in the ECM set. This is done by using a frequency memory such as a TWT combined with a delay line in a loop. The

output is gated out of the loop at successively earlier or later time, simulating range walk.

The technique employed to degrade the accuracy of the azimuth and elevation tracking circuits depends on the tracking technique that is used by the victim radar. Therefore deceptive jamming must be matched to the characteristics of the victim radar.

Typically, deception jamming can be categorized in three ways, depending on the radar parameter to be "deceived" such as; range, velocity and angle. The range gate walkoff technique represents range deception, velocity gate walkoff technique represents doppler deception and several angle deception jamming techniques are applicable to either the monopulse or sequential lobing acquisition and tracking radars. Angle deception techniques against monopulse radars can conveniently be divided into two kinds. The first category of angle jamming takes advantage of the weaknesses in the design of certain monopulse radar systems to single source jammers. Such techniques are cross-polarization, skirt frequency jamming, image jamming, etc. The second one uses multiple sources which distort the electromagnetic wave's angle-of-arrival at the monopulse antenna. These techniques utilize the weakness basic to all monopulse tracking systems. Typical example is cross-eye jamming and cooperative repeater blinking. The various deception jamming techniques are introduced in the following sections.

1. Range Gate Walkoff

Range gate walkoff (RGWO) is defined as "a self screening ECM technique for use against automatic range tracking radars that captures the victim radar's range gate, walks it off in range, and then turns off, leaving the range gate with no signal" [Ref. 7: p.115]. There are several other names for this technique: range gate capture, pulloff, grabber, grabbing, stealer, deception, dropping, dumping, selecting or confusion.

This technique is a fundamental deception ECM technique against automatic tracking radars which employ the split gate to measure and track the target range. The gate is swiftly controlled by a range servo mechanism. The width of gate is varied according to the antenna modes. In tracking mode, the

width of gate is similar in size to the victim radar pulse width. In acquisition mode, the gate will be increased in length to several times the radar pulse duration. A corollary function of the gate is to reject spurious return echo signals which are not within the gate. The range gate is accurately centered at the target return echo during normal radar operation. RGWO technique exploits the characteristics of the range gate to produce range errors. RGWO jamming is typically implemented as follows: [Ref. 7: pp.786-787].

(a) The victim radar pulse is received, amplified, and retransmitted with minimum time delay by the jammer. This provides a strong "return" signal, as a beacon would, to the victim radar receiver. A strong "return" causes the victim radar to decrease the overall receiver gain by the operation of AGC circuitry. True target signal, the "skin return", is decreased in gain and the range gate is captured by the strong jamming (beacon) signal. This phase is called the dwell.

(b) By then gradually increasing the time delay, the range gate tracks the strong repeater signal. Hence, it gradually walks off from the true target range. This phase is called walk.

(c) As soon as the jammer reaches the walk limit, it is turned off. This phase is called off or drop. When the jammer turns off, the radar has no target in the range gate and must return to the acquisition or range search routine.

(d) The procedure is repeated continuously by the jammer thereby continually interrupting range tracking and seriously degrading range tracking accuracy. The walk off rate is in the range of $1 \mu s/sec$ for up to 10 seconds.

2. Velocity Gate Walkoff

Velocity gate walkoff (VGWO) is defined as "a self screening ECM technique for use against automatic velocity tracking radars, that captures the victim radar's velocity gate, walks it off in velocity, and then turns off, leaving the velocity gate with no signal" [Ref. 7: p.145]. There are several other names for this technique: velocity gate capture, pulloff, grabber, grabbing, stealer, deception, dropping, dumping, selecting or confusion.

Some radars depend on the doppler shift of the target return echo in order to get the target velocity information. The measurement and tracking of

doppler shift is accomplished by the velocity gate. VGWO exploits the characteristics of the velocity gate, which tracks the frequency of a strong echo signal. The frequency shift operation of VGWO jammer can be achieved by the serrodyne technique using a TWT. VGWO jamming can be implemented as follows: [Ref. 7: pp.937-941].

(a) Victim radar signal is received, amplified coherently, and retransmitted to furnish a strong repeated signal, such as a beacon, to the victim radar receiver. The strong repeated signal causes the radar receiver gain to decrease because of the activation of AGC. As a result of AGC action, the real target echo signal is suppressed and the repeater captures the velocity gate of the victim radar receiver. This step is also called dwell period, as in RGWO.

(b) The doppler frequency of the repeated signal is sequentially changed, or walked, either in an increasing or decreasing direction. This will cause the victim radar to track the doppler frequency of the jamming signal rather than that of the real target. This step is the walk phase.

(c) Upon reaching the walk limit, the repeater is turned off. This will cause the victim radar to breaklock. The victim radar then returns to the acquisition mode and searches for the target's frequency again. If the victim radar fails to reacquire the real target, it may falsely lock to a spurious low level signal. This step is the off period.

(d) Above procedures are repeated through such VGWO cycle. RGWO and VGWO must be done in a coordinated manner for most efficient use of these ECM techniques.

3. Skirt Frequency Jamming

The definition of skirt jamming is that "skirt frequency jamming refers to jamming on the skirts of the frequency response curve of the radar receiver. Its effectiveness depends on unbalance between the sum and difference channels, at these frequencies, where rapid phase shifts are present in each channel. Of course, it can be effectively countered by careful design and construction of the radar" [Ref. 7: p.843].

Skirt frequency jamming can also be used with pulse repeater jamming. When the ECM set detects the victim radar signal, it will transmit a jamming signal which is offset from the victim radars frequency. This offset frequency by the ECM set will produce a beat signal with the victim radar local oscillator. The beat signal will appear on each side of the passband spectrum, or on the passband skirts. Stable phase control of the victim radars phase detector will be hard to attain because of the necessary bandpass. Consequently, the phase-tracking errors translate into angle-tracking errors by the radar.

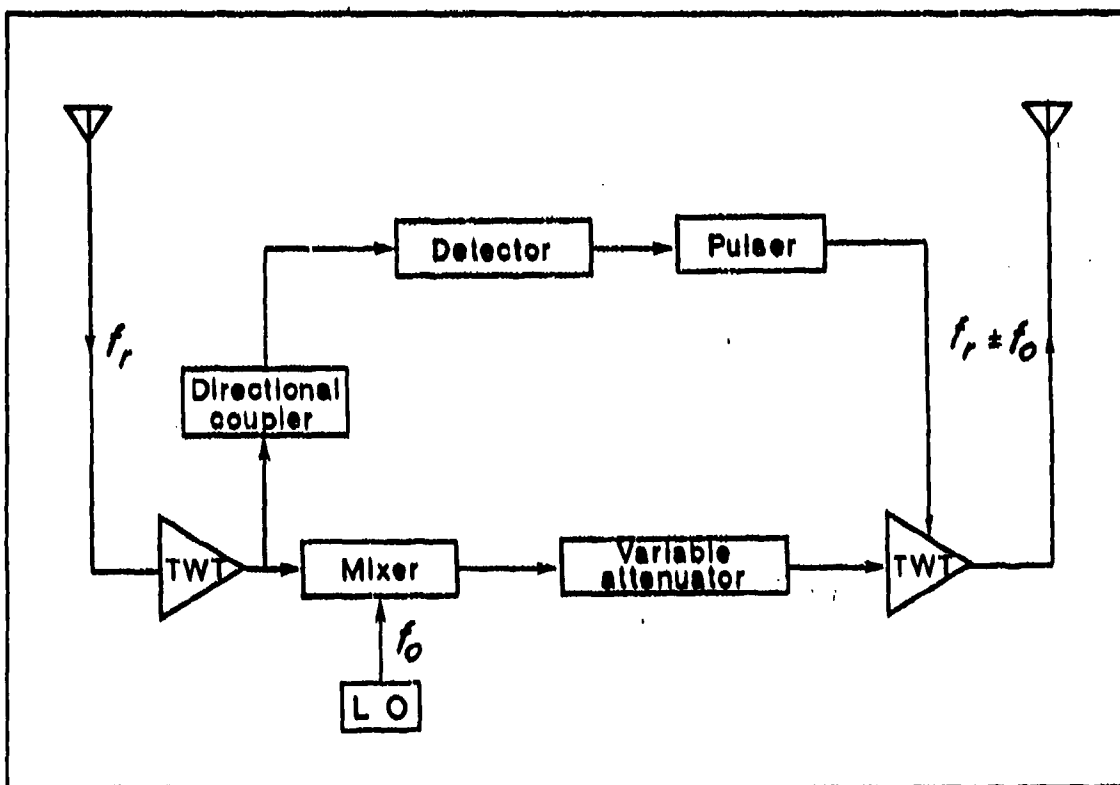


Figure 12. Block diagram of the skirt frequency jamming.

Figure 12 shows the block diagram of skirt frequency jamming. A detector provides the input signal to the pulser. When the received victim radar frequency, f_r , fed into the balanced mixer, the balanced mixer generates two sideband jamming signals at $f_r - f_o$ and $f_r + f_o$ where f_r is the center frequency of the victim radar and f_o is the local oscillator frequency of the jammer. These

jamming signals contain very little receiving signal frequency, as shown in Figure 13. The victim radar receiver will detect jamming signals at the skirt frequency where the receiver gain rolls off.

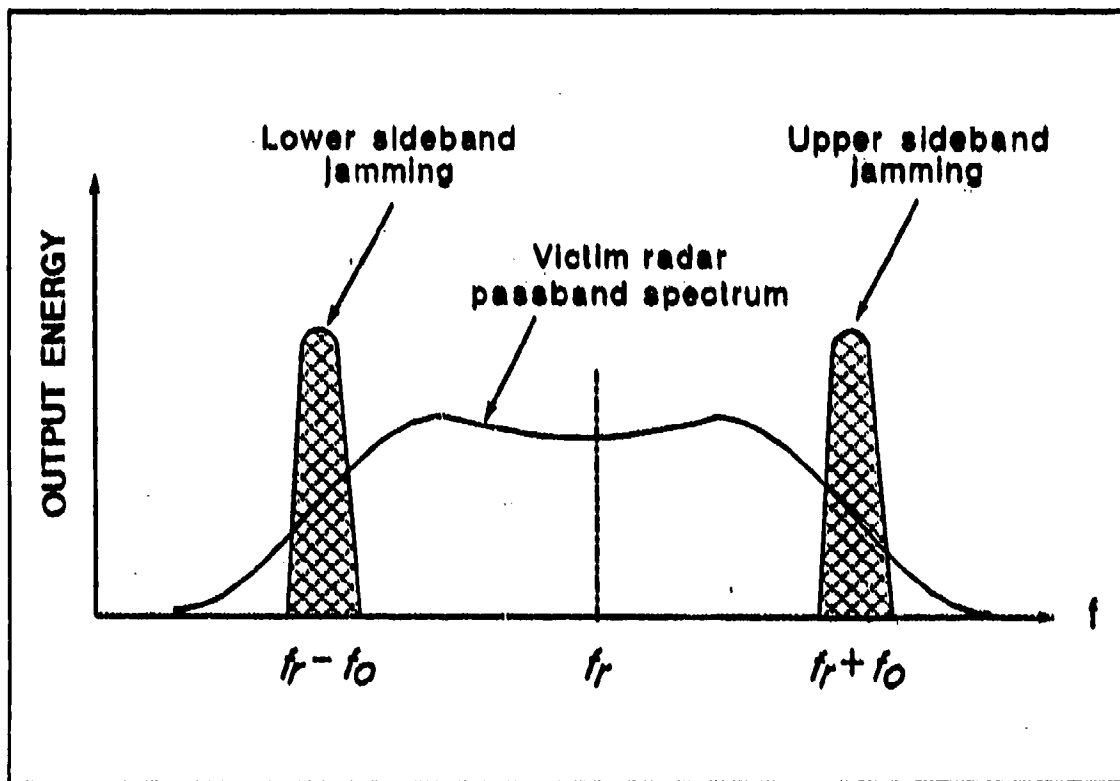


Figure 13. Waveform of skirt frequency jamming.

4. Delta Jamming

Delta jamming is a self-screening ECM technique that causes erroneous angle tracking by transmitting two RF signals at two different frequencies, f_1 and f_2 . The spacing of $f_1 - f_2$ is usually equal to the IF center frequency of the victim radar. This frequency separation can be controlled so as to make false IF signals in the victim radar IF amplifier. By forming false IF signals, the victim radar control circuits can be made unstable or will have incorrect bias.

There are several other names for this technique: dual-frequency, IF-jamming, two-line delta, or RF/IF delta.

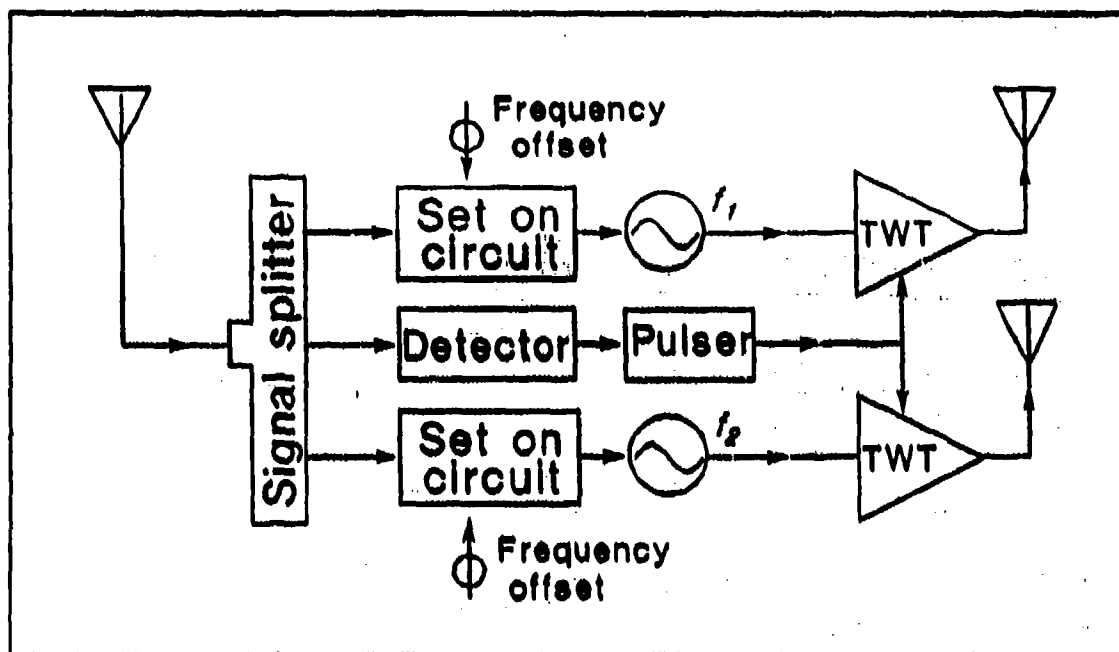


Figure 14. Delta jamming block diagram.

Figure 14 shows a delta jamming block diagram for generating two RF frequencies. Two set-on oscillators are used to lock on to the received victim radar's frequency. Frequency offset controls of both oscillators allow the locked jammer frequency to be displaced by exact amounts from the victim radar's frequency. In order to allow synchronized operation of both power amplifiers, the victim radar pulse detector circuit is used. Each set-on oscillator has its own high power TWT amplifier and radiating antenna [Ref. 7: pp.602-605].

5. Image Jamming

Image jamming is a self-screening ECM technique for use against tracking radars dependent on phase-sensing for angle tracking, as in phase-comparison monopulse radar. The definition of image jamming is as follows: "Image jamming occurs at the image frequency of the radar, depending on the fact that the phase angle at IF, between two signals (image frequency and local oscillator) is the reverse of that which would appear at the IF if the two signals were at the normal frequencies of the receiver. Since the phase-comparison monopulse determines the direction of the error by the direction of the phase difference between two

signals, image jamming causes the antenna to be driven away from the target if the jamming power exceeds the signal power" [Ref. 7: p.703].

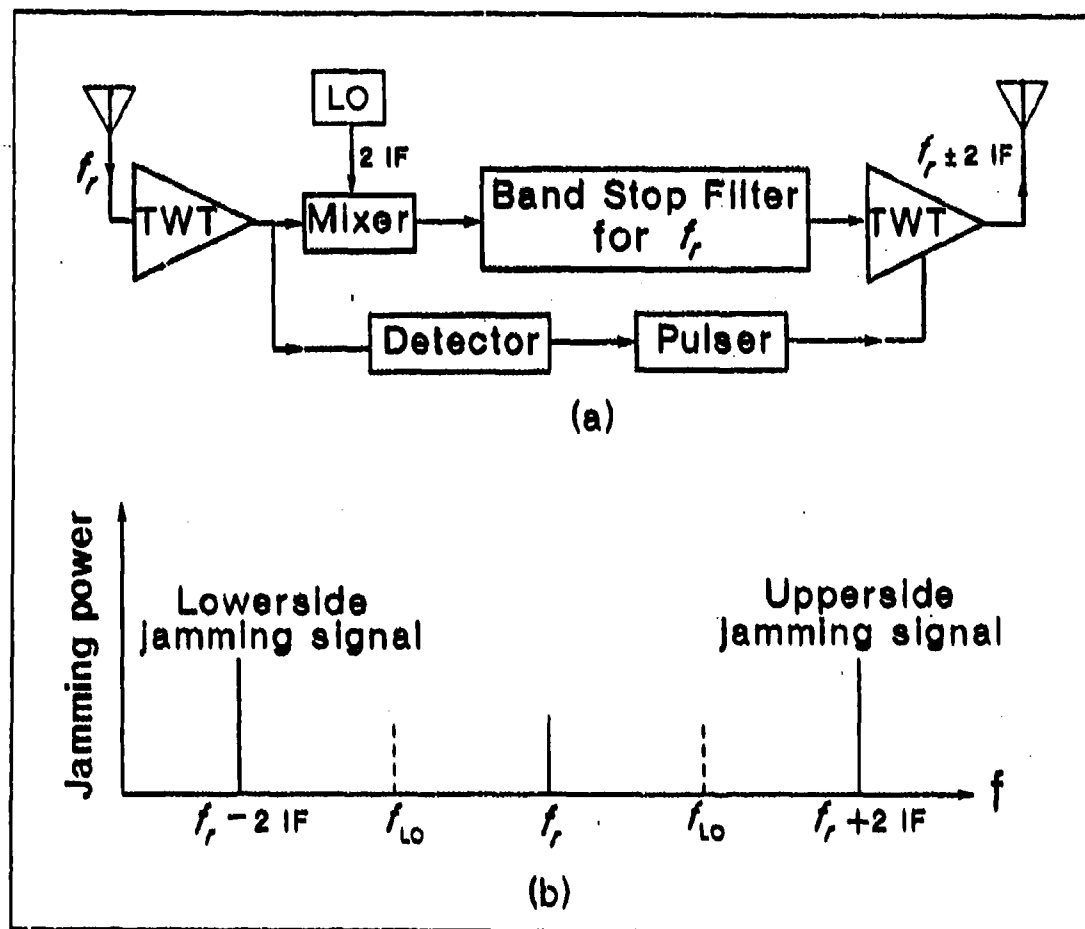


Figure 15. Image jamming block diagram and waveforms.

Figure 15 shows an image jamming block diagram and its frequency spectrum. The amplified victim radar signal through the input TWT amplifier, is fed into a mixer and an RF signal detector. Local oscillator frequency of the jammer is equal to two times the victim radars IF frequency. The RF signal detector provides an input signal for the pulser, which turns on the final pulsed TWT for every input radar pulse. It is necessary to know the victim radars IF for best operation.

In the case shown in Figure 15 (a), the band stop filter takes out the radar frequency, f_r , and then passes the lower sideband frequency, $f_r - 2IF$ and the higher sideband frequency, $f_r + 2IF$, which are used as the image jamming signals.

Figure 15 (b) shows the frequency spectrum which has the two image jamming signals which represent the lower and upper sidebands, where f_r and f_{LO} represents the victim radar frequency and local oscillator frequency respectively [Ref. 7: pp.702-704]. As an alternative, just one sideband, either the lower or the upper side of the image jamming signal, can be generated by utilizing a simple high pass or low pass filter.

6. Cross-Polarization Jamming

This is a self-screening jamming technique which causes angular error in tracking radars, including monopulse. Some monopulse radars provide erroneous angular information when the received signal is polarized at right angles to the

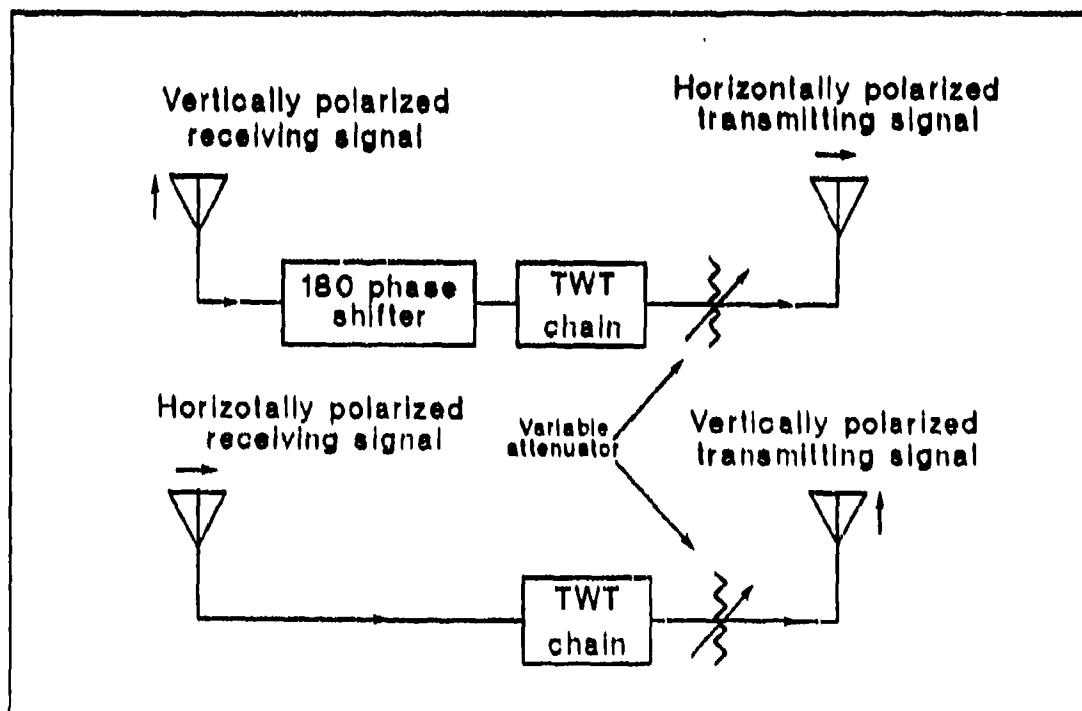


Figure 16. Block diagram of cross-polarization pulse repeater.

polarization of the radar transmitter. Cross-polarization jamming [Ref. 7: pp.579-585] takes advantage of this characteristics of those radar systems.

Figure 16 shows the repeater system employing two separated cross-polarized receiving and transmitting antennas. The horizontally polarized signal is radiated as a vertically polarized signal, and the vertically received signal is phase shifted 180° and radiated as a horizontally polarized signal.

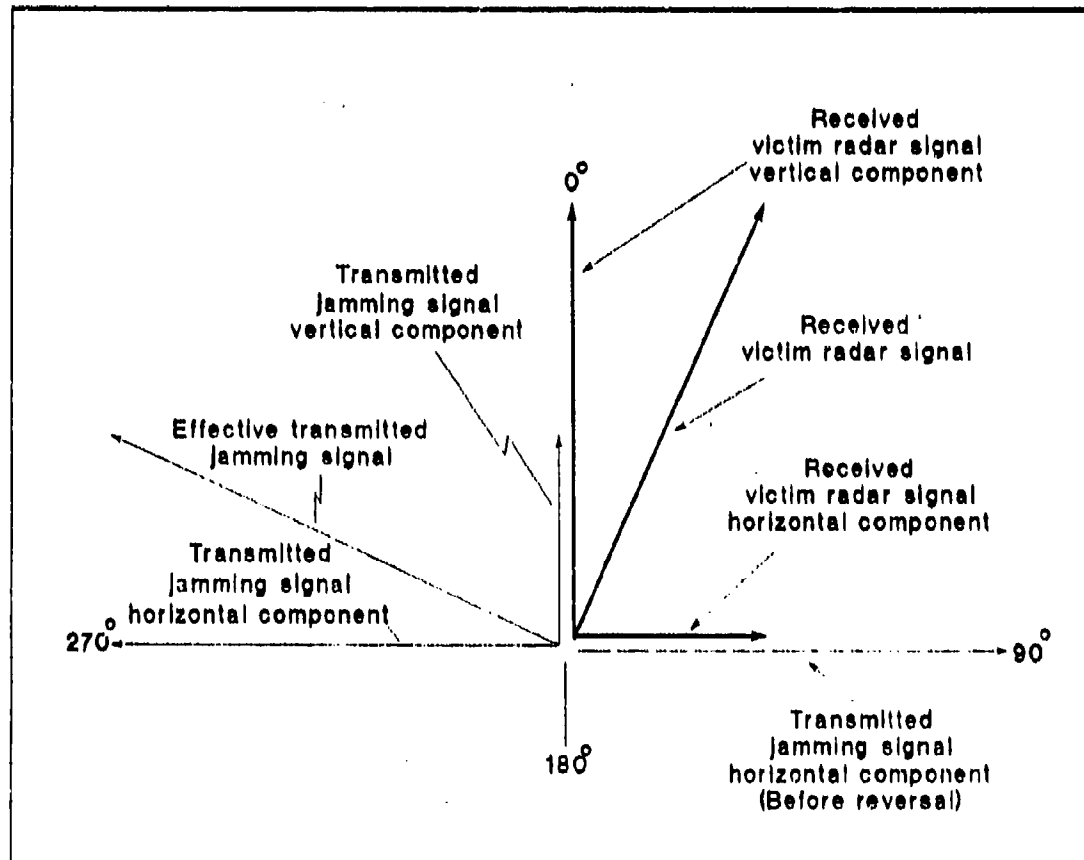


Figure 17. Components of polarization.

Figure 17 shows the polarization components of the signals. The polarization components of the victim radar signal appearing at the jamming platform are dark arrows. The horizontal polarization component of the received victim radar signal is used for producing the vertical polarization component of the jammer which is then retransmitted to the victim radar antenna through the

TWT amplifier chain without 180° phase shift. On the other hand, the vertical polarization component of the received victim radar signal is used for producing the horizontal polarization component of the jammer and is shifted by 180° , after which it is then retransmitted to the victim radar antenna through a second TWT amplifier chain. The function of the 180° phase shifter is equivalent to a 180° direction change of the electric field vector. When these modified polarization components are transmitted back to the victim radar antenna, they will superimpose as a target echo signal which is cross polarized to the skin echo.

The effects are very similar to cross-eye with a sum null on boresight, and a pair of difference nulls each side of boresight as in Figure 19 (b) and Figure 20 (b), respectively.

7. Cross-Eye Jamming

This is a ECM technique that generates angular errors in monopulse radars by radiating phase-controlled repeated pulses using separate antennas mounted on an aircraft or other platform. The concept of cross eye is to use two out-of-phase ECM sources producing either nulls or phase front angular distortion due to the interference between two jamming sources.

One method of describing the cross-eye concept [Ref. 7: pp.555-576]. is to use two ECM sources which have equal amplitudes and are 180° out of phase, as shown in Figure 18. This figure shows the aircraft approaching normal to the victim radars beam direction. The antenna mounted on the nose section is a receive only antenna which provides the victim radar signal information to the two ECM sets. The received signal is divided, amplified, and phase controlled so that the two ECM sets reradiate repeater jamming signals that have the same amplitude but are 180° out of phase with each other. The two jamming signals will make a null at the center of the victim radars antenna aperture.

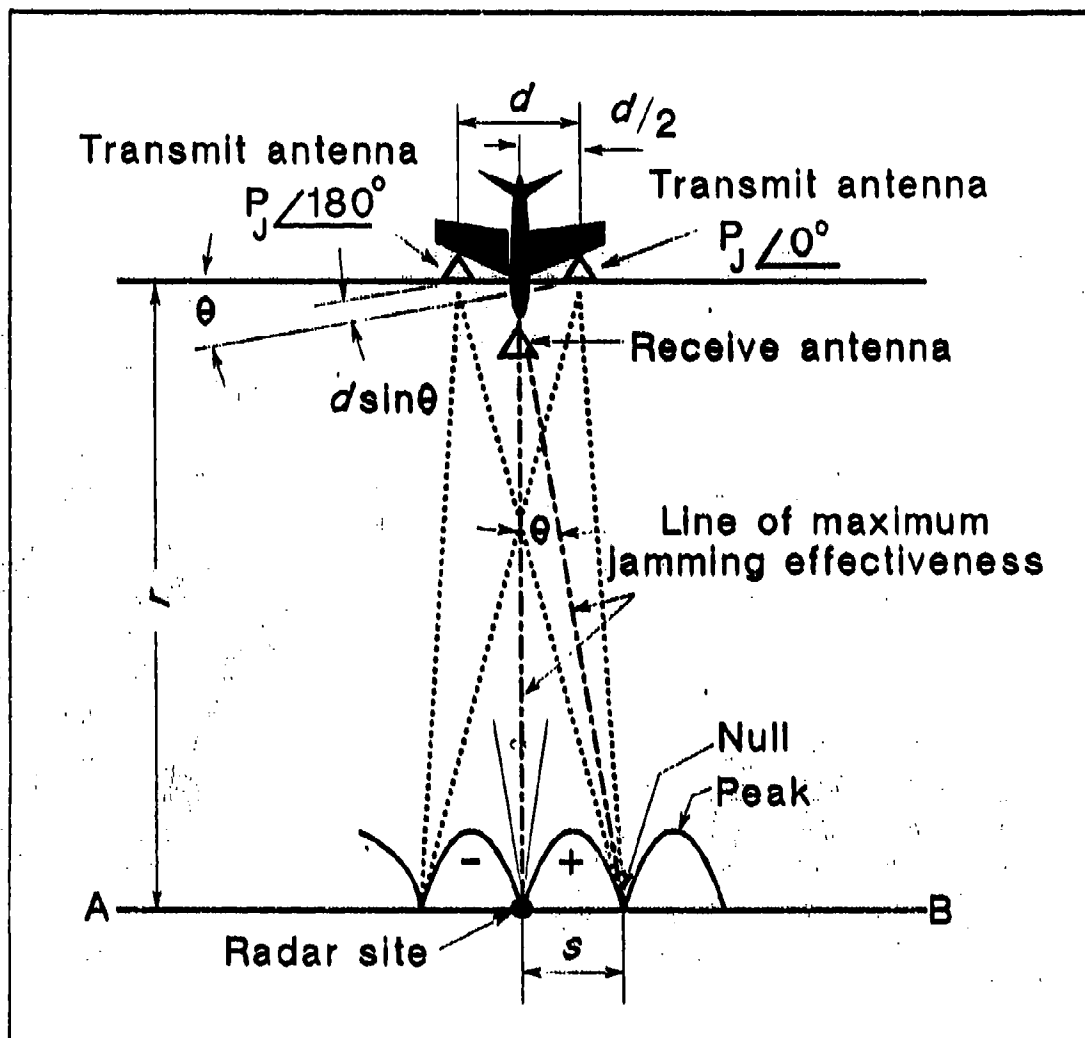


Figure 18. Cross-eye concept applied to a radar.

The two transmitting antennas are installed d feet apart, typically one on each wing. Thus the signal transmitted by the left wing antenna will travel $d \sin \theta$ more than that by the right wing antenna, making the first right side null point on line AB . Line AB represents the fact that the radar doesn't have to be looking perpendicular to the jammer baseline for cross-eye to be effective. The nulls will occur whenever $d \sin \theta$ equals $n\lambda$ where n is any integer and λ is the

radar wavelength. For finding the null positions, two equations can be derived as follows:

$$n\lambda = d \sin \theta \quad (3.1)$$

$$s = r \tan \theta \quad (3.2)$$

For the first null, n should be one. Solving for θ and s , ($\sin \theta \approx \tan \theta = \theta_{rad}$ when θ is small):

$$\theta = \tan^{-1}\left(\frac{\lambda}{d}\right) \approx \frac{\lambda}{d} \quad (3.3)$$

$$s \approx r\theta = r \frac{\lambda}{d} \quad (3.4)$$

where θ is the first null angle at the aircraft

s is the null distance from the centerline

r is the distance from jamming aircraft to victim radar.

The relationship between s , r , and d can be explained from the equation (3.4). As the aircraft moves closer to the radar site and/or the distance between two ECM sets is increased the spacing between nulls, which is related to the jamming effectiveness, is decreased.

When cross-eye jamming is operating, the victim radar receiver detects steep spatial jamming lobes of opposite polarity on either side of the centerline, or any other null. These lobes are detectable because the jammer signal is stronger than the skin return and result in angular tracking errors (usually azimuth) of a few degrees at most.

The following figures show the relative signal voltage vs scan angle, which is useful for the understanding of cross-eye jamming.

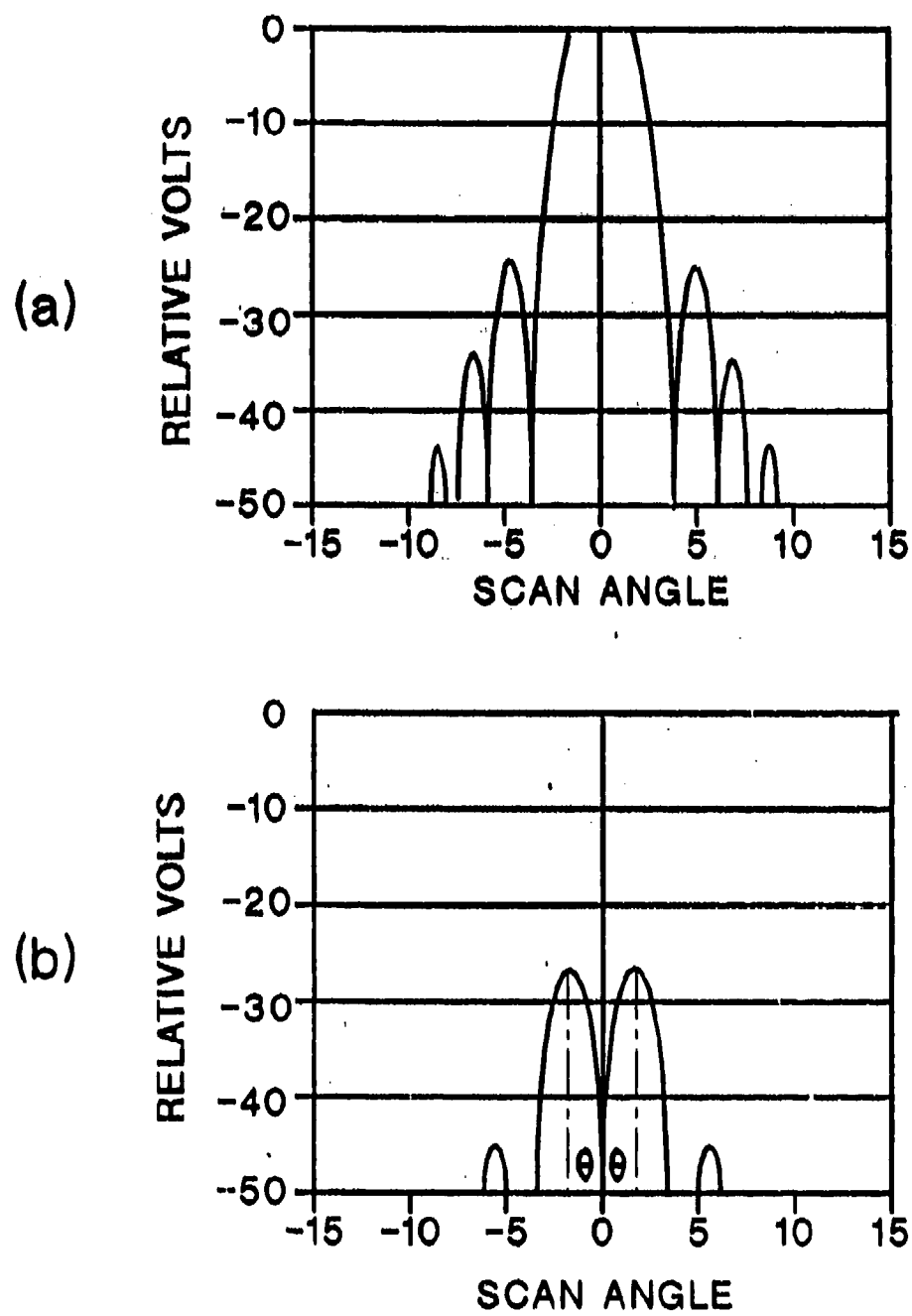


Figure 19. Sum channels for monopulse receiver. (a) One source. (b) Two sources.

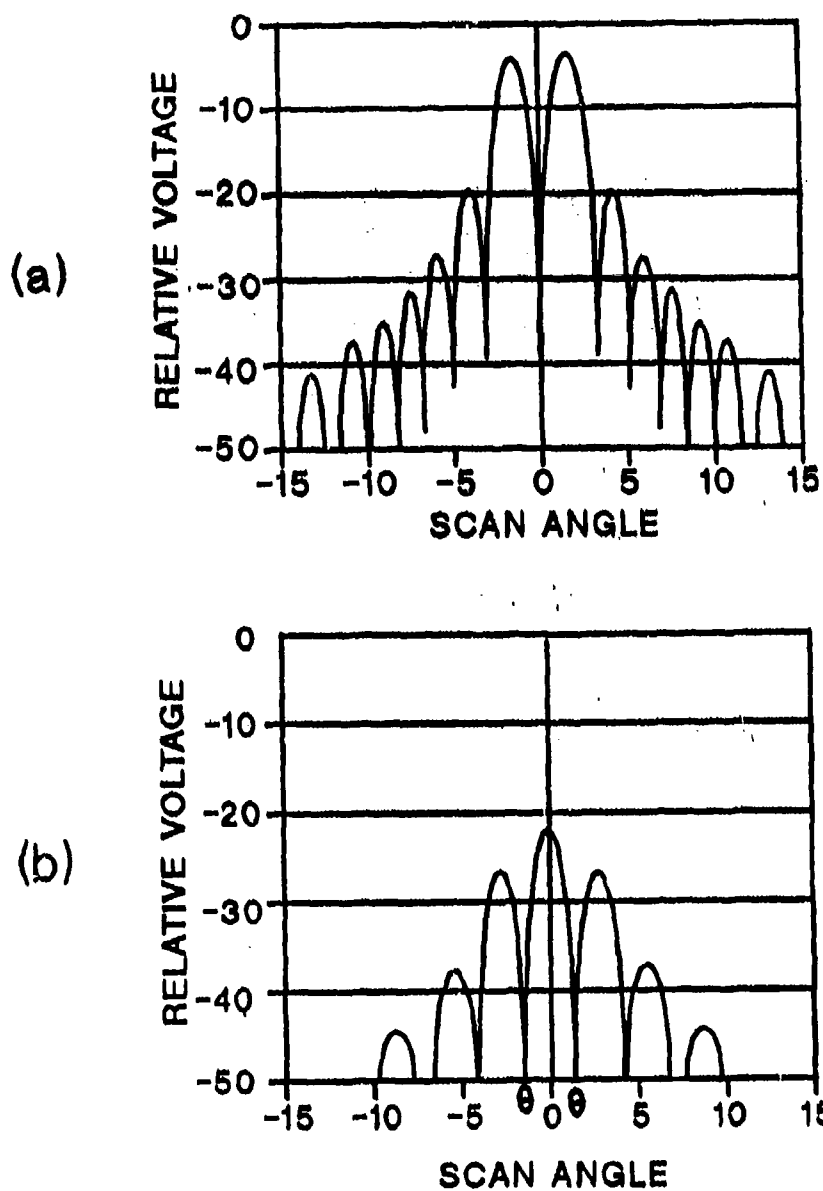


Figure 20. Difference channels for monopulse receiver. (a) One source. (b) Two sources.

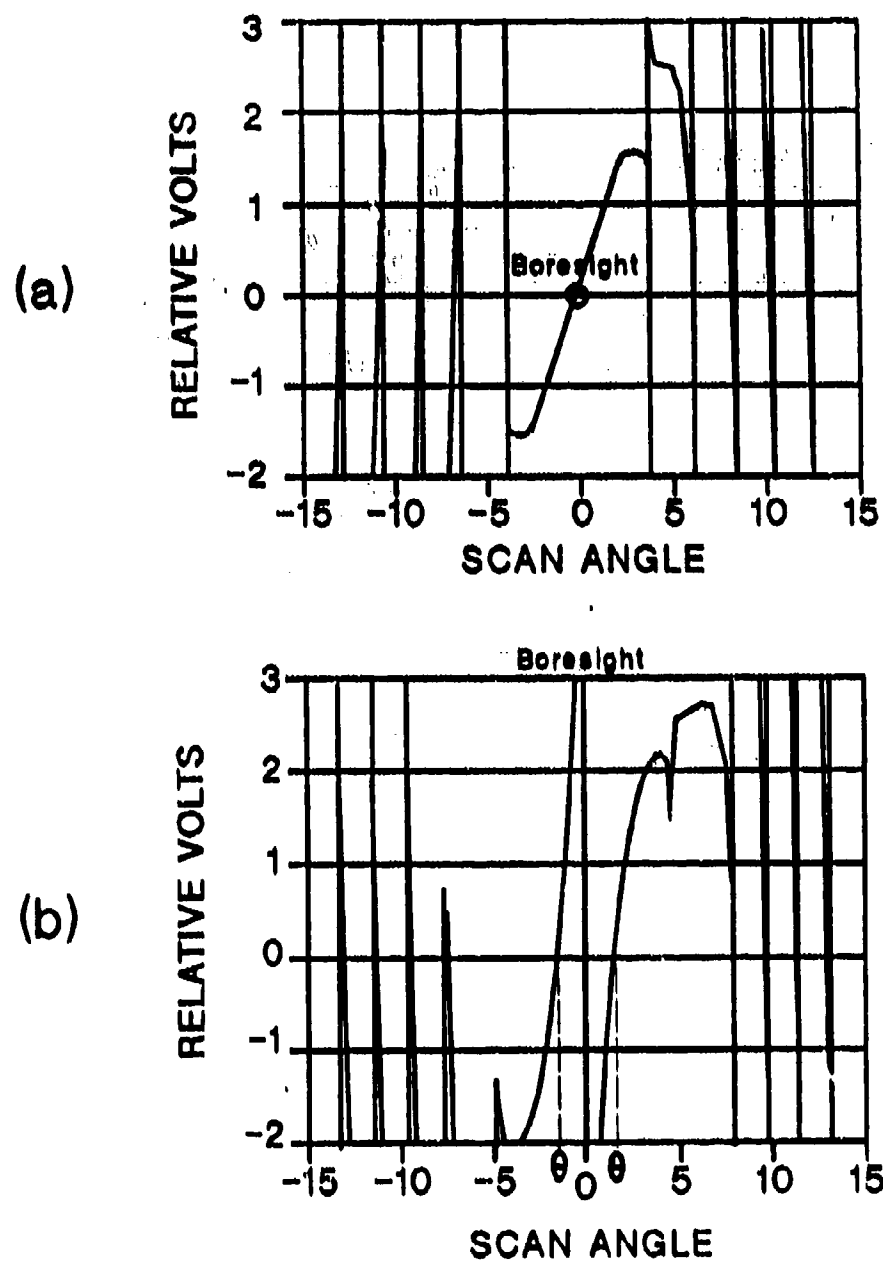


Figure 21. Patterns of the difference channel divided by sum channel. (a) One source. (b) Two sources.

Figure 19 shows the sum channel. There is no null point on the boresight axis for one source (a), but two sources (cross eye) produce a null on the boresight axis (b). Figure 20 shows the difference channel. There is a null point on the boresight axis for one source. But two sources have two null points, each at the cross-eye angle (θ_{CE}) on both sides of the boresight axis. Figure 21 shows the difference channel divided by the sum channel. Figure 21 (a) corresponds to Figure 3 (d). Figure 21 (b) is the result of cross-eye so that the nulls move, one to each side of boresight. Thus the radar can track either null in Figure 20 (b) and Figure 21 (b). The angle error (θ_{CE}) caused by cross-eye is never large.

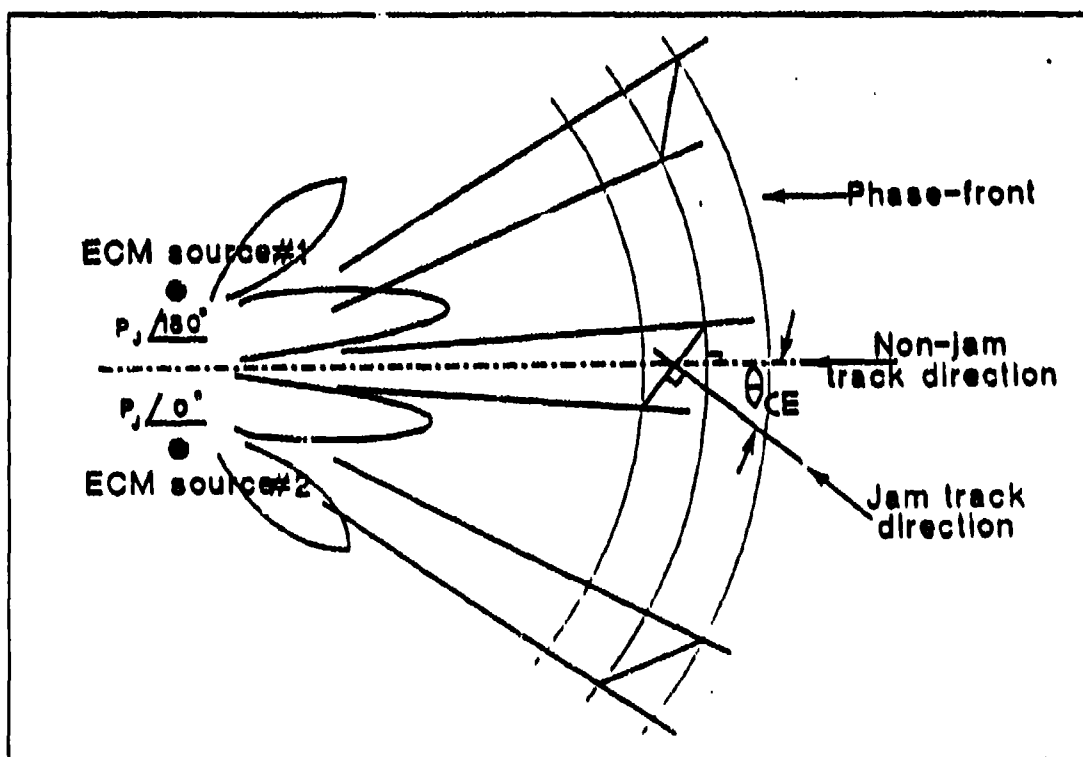


Figure 22. Warped phase front.

Another way to describe the cross-eye concept is phase front distortion. Under cross-eye conditions an interferometry pattern is produced as shown in Figure 22. This concept utilizes the the property of any radar tracking antenna

which is to be aligned with the face parallel (actually tangent) to the wave front of the signal being tracked. The distorted phase front of the electromagnetic wave is shown in the interferometry pattern Figure 22. The victim radar antenna will align itself with the boresight normal to the distorted phase front, resulting in angular tracking error. Therefore cross-eye is also known as phase front distortion. The peaks in Figure 18 correspond to path length differences of $n\frac{\lambda}{2}$ and represent the phase front distortion shown in a plan-view in Figure 22.

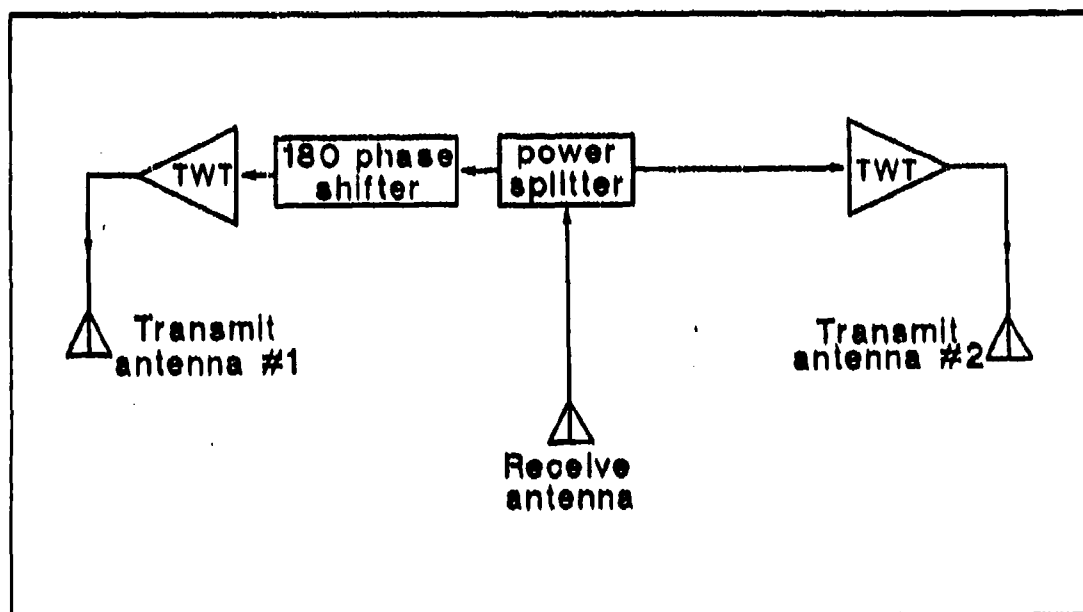


Figure 23. Block diagram of basic repeater type cross-eye system.

A block diagram of a cross-eye system, which employs a repeater, is shown in Figure 23. The basic concept of the system operation is the same as the previous explanation. A center receive-only antenna feeds a TWT amplifier whose output power is split so as to drive two transmitting antennas with 180° out of phase signals. However, the system shown in Figure 23 has a basic problem in that the perpendicular bisector of the line joining the two ECM antennas must continuously intersect the radar site so as to maximize cross-eye jamming effects. Any maneuver incurring antenna yaw will degrade the jamming

effectiveness. In order to eliminate this problem, two separate, automatically compensating repeater paths are used as in Figure 24. The relative placements of the two transmit and receive antennas result in automatic path length compensations. Thus the two signals radiated by the jammers will remain 180° out of phase at the victim radar regardless of the angle of arrival of the victim radar signal at the jammers i.e., no yaw dependency.

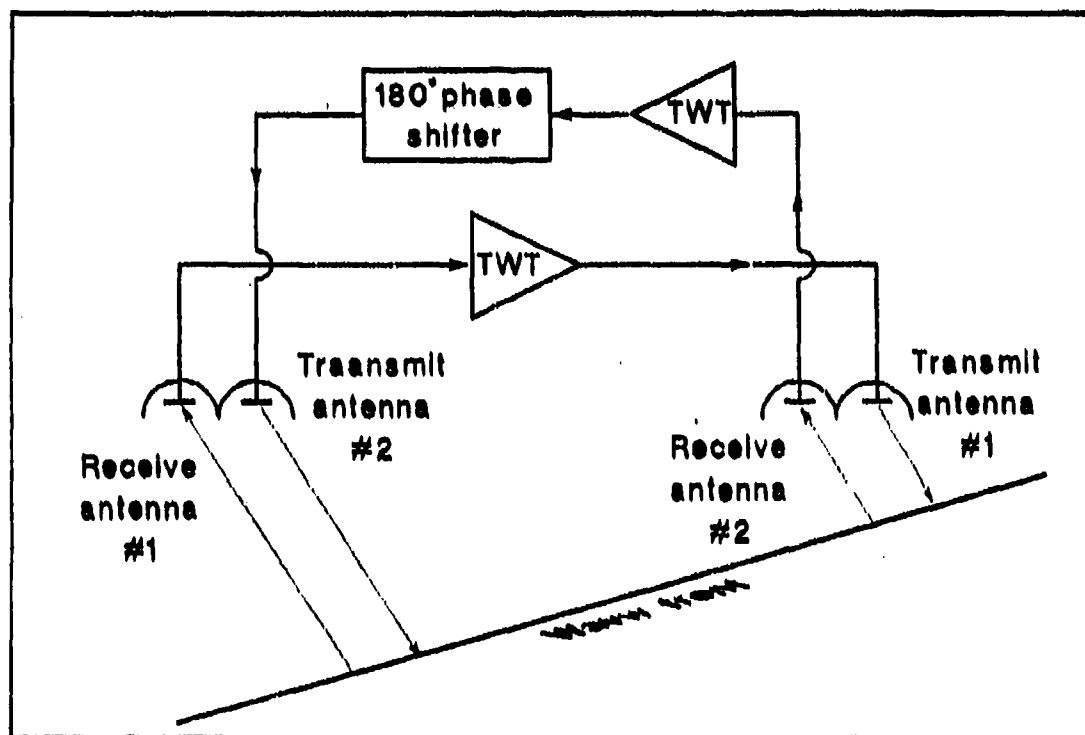


Figure 24. Block diagram of cross-eye system using two separate repeater path.

C. PASSIVE COUNTERMEASURES

1. Chaff

Chaff is one of the earliest radar ECM devices, also known as "window" in the UK. It is still a very useful technique, applicable to nearly all radars except some moving target indicator (MTI) radars.

Chaff consists of resonant dipoles, used to reradiate RF energy, to generate multiple echo effects and false targets on the radar display. According to the electromagnetic theory of chaff, a piece of chaff acts like a dipole whose

output terminals are short circuited. In the case of a dipole, the greatest reradiation occurs when the dipole length is approximately a half wavelength of the incident RF energy [Ref. 9: p.3L-3]. Therefore by cutting to a half wavelength of a specified RF frequency, maximum effect by the chaff will be attained.

Materials used for chaff are conducting or nonconducting fibers coated with a conducting material like aluminum or zinc. The general forms are ribbons of aluminum foil, silver-coated nylon thread, and glass fiber coated with a conducting material. The thickness of a foil should be as thin as possible, because the falling rate decreases the thinner the foil.

Chaff length is proportional to the wavelength. If the frequency is high or wavelength is short, chaff length should be short. If the frequency is low or wavelength is long, chaff length should be long. Long chaff length increases its falling rate. Chaff is not used much below 1GHz for this reason. To cover B, C band radars, rope is often used instead of chaff [Ref. 9: p.3L-7].

Chaff can be applied in combination with other jamming techniques to upgrade the effectiveness of jamming. Various chaff missions are also possible. Representatively, these involve chaff corridor screening, chaff confusion and saturation, chaff deception, signal attenuation, and self-protection missions.

Chaff corridor screening missions deny strike aircraft information inside the corridor to the victim radars. Chaff confusion and saturation missions overload the victim radar scope with false echoes returned by the chaff. Thus the victim radar operator cannot discern the true targets on his radar display. Chaff deception missions create signals like true targets on the radar displays. To achieve this mission, chaff cloud size should be greater than the radar cross section (RCS) of individual targets by an amount equal to the expected MTI improvement factor of the victim radars. In this way effective returns from the chaff after MTI processing should be similar to the returning echo signal from the aircraft targets. Signal attenuation missions reduce target detection ranges of the victim radars. To achieve this purpose, chaff clouds must have large chaff density per unit volume at the victim radar frequencies. The result is the effect of a

greatly increased propagation loss because of the intense back scattering of the radar forward energy. Self protection missions deploy chaff in order to cause the victim radars to break lock on own aircraft. The effectiveness of this technique will be increased when accompanied by a simultaneous evasive maneuver [Ref. 10].

2. Radar Absorbing Material

Radar absorbing material (RAM) is used to reduce the RCS by absorbing impinging electromagnetic energy. Thus, the reduced target size will apparently be decreased, along with the target detection range.

One type of RAM is made by using a radar semitransparent layer on the surface of the vehicle. The reflected and transmitted energy (50% each) recombine destructively at the surface, resulting in up to 20dB RCS reduction. This is good only in a narrow band due to the fixed thickness of the semitransparent layer [Ref. 11: p.101]. (approximately $\frac{\lambda}{4}$)

Another type of RAM is a dissipator, which attenuates the incident electromagnetic wave [Ref. 7: p.405]. This absorber can reduce the energy reflection over a wider frequency band, but is usually thicker.

Still another type of RAM is an absorbent paint, containing microscopic particles of an iron compound in the ferrite family. Absorbent paint can give RCS reductions of up to 20 dB. It is used for absorption mostly above 10 GHz. Such paint can be applied to almost any aircraft surface but there is still a weight penalty [Ref. 12: pp.49-50].

3. Stealth

Stealth has been a highly classified technology until now. It combines RAM techniques with others and can be applied to any kind of weapon system which can be detected by radar, including aircraft.

RCS is not the only concern in stealth technology. The design concept of the stealth aircraft also includes avoidance of detection by infra red (IR) scanner, optical, acoustic, smoke and contrails [Ref. 13: p.28].

In reference to radar ECM, however, the only interesting point of the stealth aircraft is related to detection evasion by enemy radar. For that reason,

RCS reduction plays an important role in stealth aircraft. In order for stealth aircraft to reduce RCS, RAM and counter reflective geometry can be employed. RAM, as discussed above, contributes to RCS reduction by absorbing or attenuating incident electromagnetic energy. In addition, radar absorbing structures (RAS) and radar transparent structures, which are constructed of composite materials, are used to reduce weight as well as RCS. Two geometric methods are used to scatter the radar beam, rather than reflect it, from the surface of the stealth aircraft. "One is to make the shape flat or rectilinear, concentrating the reflection on one bearing, and reducing the tendency for concave surfaces to function as retro reflectors over large ranges of angles of incidence. The other is to scatter the wave with a carefully designed concave curve of constantly changing radius, so that each tiny part of the surface has its own tiny main-lobe reflection." [Ref. 14: p.22]. Two kinds of stealth aircraft have been introduced recently by the USAF. F-117A, a stealth fighter, is based on the first method, and the B-2, a stealth bomber, combines both methods.

D. DECOYS

Decoys are a support ECM techniques that utilize low cost vehicles equipped with different jamming augmentation systems. Decoys can be employed by a variety of techniques using different delivery vehicles employing a variety of jammers. Typical examples of this tactics application are expendable jammers and remotely piloted vehicles. These jamming techniques are not peculiar against monopulse radar systems, but are commonly applied to any radar.

1. Expendable Jammer

Expendable jammer (EJ) consists of the jammer and its delivery package, such as parachute, rocket, expendable drone and remotely piloted vehicle (RPV). Most EJ are small, light weight, and cheap. Output jamming power of one unit may not be adequate to jam a given radar, therefore, several EJs may be required to achieve satisfactory radar capture by decay. By definition, EJ is not recovered for reuse. This is quite different compared with a recoverable RPV.

The most important factor, therefore, in EJ employment is cost effectiveness. To be cost effective, the life cycle cost of EJs should be less than that of

the platform and alternate ECM, which the EJs are protecting. The tactics of EJ employment are very flexible, lending to a variety of scenarios of delivery package and attached jammer. EJs are dispensed in several ways. Aircraft deploy them by using forward fired rockets, free fall, parachute retarded or by towing. When delivering EJs, if the delivery package does not have flying capability, parachutes can be used to lengthen jamming time.

2. Remotely Piloted Vehicle

This tactic utilizes a drone RPV as ECM support, to assist strike aircraft and to confuse enemy radar. RPVs can perform various missions such as jamming, chaff dispensing and EJ delivery.

RPV effectiveness as a tool of EW was demonstrated during the 1982 conflict between Israel and Syria in the Bekaa Valley, even though not used for decoy delivery but for remotely controlled reconnaissance [Ref. 14: p.112] and aircraft simulation. RPVs as decoys utilize small radio controlled drones. The use of RPV is very cheap compared with using manned aircraft.

The primary advantage of the RPV is use in a high threat environment without loss of personnel and expensive aircraft. RPVs are more difficult to detect and shoot down than manned aircraft due to their small size. Even though RPVs are small, RCS enhancement can be used to confuse or deceive enemy radar.

E. DESTRUCTIVE COUNTERMEASURES

1. Anti-Radiation Missile

The effectiveness of SAM systems is mainly governed by the precise target position information. For this reason, most SAM systems are required to have targeting radars. These radars greatly enhance the capability of SAM. Meanwhile, SAM systems become vulnerable targets of the anti-radiation missile (ARM) by working as active emitter.

In the case of high-speed anti-radiation missile (HARM), the most recently developed ARM in the US, operation is by locking onto enemy radar radiation signal either before or after launch. Onboard RWR or the missile guidance section can detect the enemy radar signal, then the missile is locked on

and homes on the radar. HARM has a wideband seeker which covers all radar bands from 2 to 40 GHz, and has an extensive parameter threat library (pulse width (PW), PRF). HARM has three launch modes which provide flexibility of employment, depending on the tactical situation [Ref. 14: p.930].

In stand-off mode, HARM can be fired on a trajectory for maximum range from high altitude. The highest-priority threat signal is selected and the location is memorized. Then accurate inertial navigation system (INS) allow HARM to continue the attack even if the radar system is turned off after the launch of missile.

In target-of-opportunity mode, the received threat signals are displayed in the cockpit. Pilot can select the radar target.

In self-protection mode, the radar warning receiver (RWR) detects, sorts, and indicates immediate threats to the aircraft.

Because of these characteristics, HARM is capable of coping with many SAM radar threats.

2. Wild Weasel Tactics

"Wild Weasel" is a nickname for an aircraft which performs special missions relating to destruction or suppression of enemy air defense systems. Their primary mission is to provide a safe corridor for the air strike forces using integrated weapon systems. In order for the Wild Weasel to carry out this kind of mission, it needs a sophisticated electronic equipment such as a launch computer system, specialized radar warning and location system and ARM or other destructive weapons.

Wild Weasel aircraft have been continuously updated by the improvement of technology. The US Wild Weasel aircraft were F-100Fs and F-105Gs. In the beginning of Vietnam war, F-100Fs Wild Weasel aircraft were equipped with an unsophisticated radar warning system designed to intercept and home in on the SA-2 radar signal. It could only detect one target signal at any one time. They had to directly home in on the SAM radar site until the crew visually located the site, then come back again and drop conventional bombs on the area in an effort to destroy the SAM systems. This tactic was extremely dangerous

because the crew couldn't detect any other sites near that the area [Ref. 15: pp.20-26]. However, low level attack of the Wild Weasel in those day was very effective in devastating enemy SAM sites. In 1966, Two-seat F-105G aircraft with shrike ARM replaced the old Wild Weasel.

After Vietnam, F-4Gs, following F-4Cs, became the primary Weasel aircraft. The F-4G Wild Weasel aircraft is a modified version of F-4E aircraft. For F-4G Wild Weasels, an airborne RWR was installed instead of 20mm nose gun in the F-4E. This RWR can detect and locate the enemy radar emitters, and identify each threat such as SAM or AAA sites. Wild Weasel then attacks the selected target from outside lethal range. USAF is considering F-15 or F-16 aircraft as future Wild Weasels.

IV. ANALYSIS OF ECM TECHNIQUES

A. DENIAL JAMMING

Denial jamming or noise jamming is not the most efficient method to use against tracking radars because most tracking radars are able to maintain angle tracking by locking on to the noise jamming source. Applying noise type jamming to tracking radars may increase the vulnerability of the jamming aircraft since the jamming source may act like a beacon signal [Ref. 16: p.138].

The principal effect of the noise type jamming against monopulse radar is to deny the target range information. In monopulse radar systems, denial jamming will deny range information if the jam-to-signal ratio is equal or greater than one. A missile system utilizing monopulse radar guidance may or may not be able to effect a kill without range information, depending on system performance specifications or missile launch range. However, the operating effectiveness of the ground missile system will be degraded without providing accurate range data, even though modern missile guidance systems can operate with angle data only.

The main advantage of noise jamming is that precise information about the victim radar system is not required. One needs to know only the center frequency and bandwidth of the victim radar to perform denial jamming. Generally speaking, noise jamming is less efficient than deceptive jamming methods because denial jamming does not accurately match the parameters between the jammer and the victim radar. Thus the circuitry for denial jamming is simpler than that for deception jamming. The simpler circuitry generally implies lower cost.

The effectiveness of noise jamming techniques such as swept spot, barrage and blinking, described in chapter three, is hard to quantify. The jamming effectiveness may be differently evaluated depending on the tactical situation and available information about enemy weapon systems performance. However, these kinds of noise jamming will at least effectively degrade the performance of any radar against which they are employed.

1. Swept Spot Jamming

The advantage of swept spot jamming is that it can concentrate the high jamming power on each victim radar while sweeping across a wide frequency band. The disadvantage is that the jamming is intermittent due to the sweeping time. This drawback can be reduced by increasing the sweeping rate. Swept spot jamming with fast sweeping rates produces approximately continuous jamming effects. Again, the optimum rate corresponds to the victims bandwidth, inferred from measurements of his pulse width.

2. Barrage Jamming

The use of this type of jammer is attractive because frequency agile radars can be jammed without readjusting the jamming frequency, as well as because a number of victim radar receivers can be jammed at the same time.

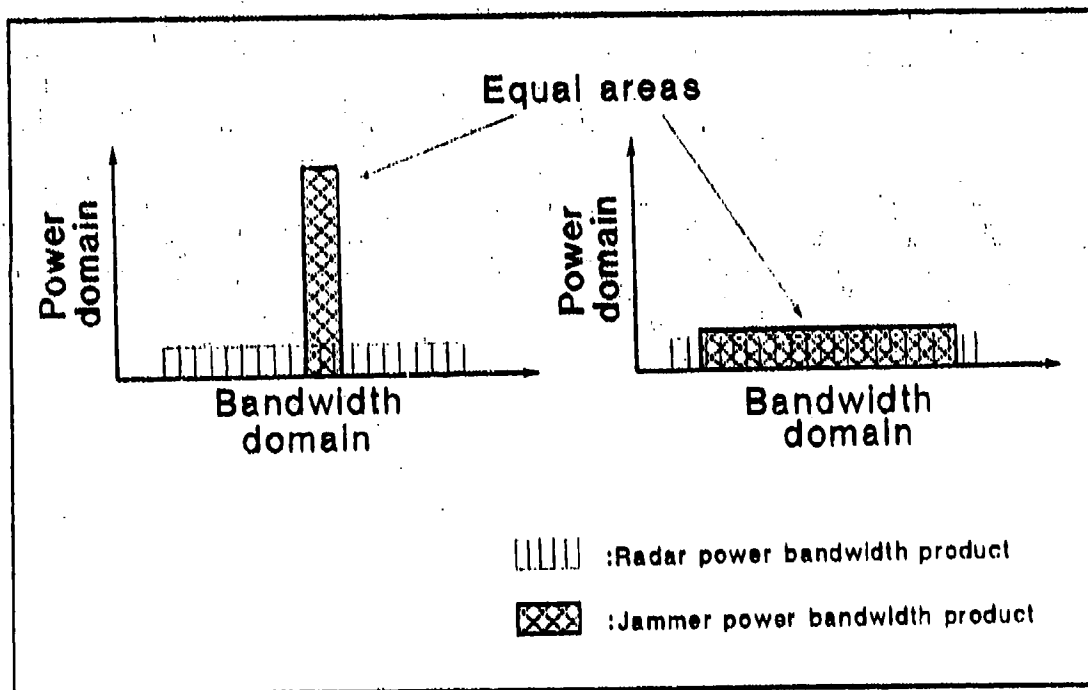


Figure 25. Barrage jamming power vs bandwidth.

As shown in Figure 25 the disadvantage of barrage jamming is that the jamming power density is diluted by being spread over a wide frequency bandwidth. The power density of barrage jamming is inversely proportional to its

bandwidth. The jamming effectiveness depends on jammer power density. If jamming power is constant, the wider the jammer's bandwidth the lower the power density [Ref. 17: pp.52-54].

3. Blinking

This is one of the most effective ECM techniques available to the ECM designer for protecting a formation of aircraft, because it works against any type of tracker including the monopulse tracker.

The disadvantage of blinking jamming is the difficulty in determining the optimum blinking rate, even though the best rate is undoubtedly on the order of the tracking servo bandwidth, or in the 0.1 to 10 Hz range [Ref. 16: p.156].

B. DECEPTION JAMMING

Deception jamming is generally implemented in the form of the self-screening ECM mission in order to jam against missile guidance which utilizes tracking radars [Ref. 16: p.138]. Self-screening or self-protection jamming is more applicable to the attack aircraft due to the jamming power and the physical size limitations on the jammer.

Deception jamming requires significantly less power to jam a radar compared with noise jamming. This is because deception jamming uses a waveform matched to the victim radar. Small size is desirable to afford more room for armament loading. In addition, lower power availability requires the jammer to be small size.

Deception jamming techniques discussed in chapter three have different jamming characteristics. RGWO as range deception technique is easy and relatively efficient way to jam against monopulse radar because monopulse radars use a conventional range gate for measuring the distance from radar to target. VGWO as velocity deception technique is a useful way to induce false doppler frequency shift. As a result, the victim radar can get false range rate information. In general, angle deception is difficult to achieve against monopulse tracking radars compared with sequential lobing radars. Monopulse techniques are inherently strong against angle deception jamming because they use simultaneous beams to determine the target position. In order to enhance jamming

effectiveness, it is imperative to closely combine these three categories of deception ECM (DECM) techniques with one another.

Meanwhile, deception jamming systems employ complicated circuits to match the characteristics of each type of system to be jammed. Complexity of system will demand more expenditure. To properly match the jamming parameters between the jammer and the victim radar systems, these techniques will require specific information about the victim radars. If such information is not available, it may greatly impact on the use of deception jammers.

1. Range Gate Walkoff

False target range information in the missile guidance and tracking radar, such as SAM targeting monopulse radar, can produce aiming-guidance error. However, target angle information is still good enough to direct against the target angular position. The radar can guide the semi-active missile with target angle information only.

In monopulse radar application of RGWO, followed by dropping of the deceptive signal, the result can be a partial loss of information. If angular deception is not simultaneously used, the victim radar will reacquire the skin echo too fast.

2. Velocity Gate Walkoff

VGWO technique is very similar to RGWO technique. But RGWO by itself may not be effective against some radars which employ target doppler measurements because those radars constantly check the target velocity data by differentiating range data and comparing to measured target doppler data.

In order for the victim radar not to reject the jamming signal by way of doppler filtering, VGWO should be combined with RGWO and angle deception technique. If the victim radar doesn't exploit the doppler characteristics, the effects of VGWO is very little.

3. Skirt Frequency Jamming

The jammer used in skirt jamming is a little detuned from the victim radars frequency. Well designed monopulse radars do not have vulnerability to this jamming because this technique basically uses the weakness in the design of the

monopulse tracking systems. The tracking accuracy of some monopulse systems is degraded if the receiver is not properly tuned to the echo signal so that the echo signal lies in the skirts of the IF filter.

4. Delta Jamming

Delta jamming technique needs high powered TWT amplifiers and high gain antennas in each channel in order to overcome the high losses by the mixers and bandpass filters of the monopulse victim radars. For effective jamming, the information on the victim radars IF bandwidth and IF control frequency are required.

5. Image Jamming

This jamming is not a dependable jamming technique because it is ineffective if the monopulse radar is equipped with an image rejection filter or mixer.

6. Cross-Polarization Jamming

One advantage is that the cross-polarization ECM technique does not need special knowledge about the victim radar. This provides design freedom which is important in the rapidly changing field of enemy missile radar control technology.

The critical drawback of the cross-polarization jamming is a need for huge jamming to signal ratios approaching 20 to 40dB [Ref. 16: p.123]. This is because the wave guide components of the victim radar highly attenuate a cross polarized signal.

In addition, any deviation in the polarization of the jamming signal results in a component with normal polarization. If the normal polarization component is greater than the cross-polarization due to the attenuation, the jamming signal will act as a good target beacon.

It has thus far been impractical to employ cross-polarization as the angle deception jamming technique against monopulse tracking radars.

7. Cross-Eye Jamming

The magnitude of angular error is determined by separation distance, phase shift, and amplitude ratio of two ECM sources. Maximum jamming effectiveness can be obtained when the jamming signals of the two ECM sources

are transmitted with 180° phase shift and at equal amplitudes. Even though the separation distances cause proportional angular error, it is difficult to implement to much effect on the jamming effectiveness because of the limited aircraft wing span. Separation has an extremely small value compared with the victim radar range.

The disadvantage of cross-eye jamming, using one receiving antenna, is dependency on the motion of the jamming aircraft. The phenomena of warped phase front occurs near the interferometer peaks. Aircraft movement by yawing will shift the interferometer null pattern, therefore jamming effectiveness can be greatly degraded. Although this fault can be eliminated by using a cross-eye system which employs two separate repeaters with equal path lengths, this technique is impractical due to cost, weight and complexity constraints.

In order for cross-eye to be effective, high jamming-to-signal is required, as much as at least 20dB [Ref. 16: p.123]. This is partly because the victim radar antenna aperture is relatively small compared with the null spacing.

Another major drawback is that the angle error produced by cross-eye is generally very small.

C. PASSIVE COUNTERMEASURES

1. Chaff

Even though MTI radar systems can provide some countermeasures against chaff, chaff is still widely used in military jamming systems. Chaff can jam wide bandwidth radars by using different lengths of chaff in the same dispenser. Some chaff dispenser systems mounted on aircraft can cut chaff to the proper length in order to match detected victim radars frequency accomplished through use of RWR.

Another advantage of chaff is cost effectiveness. Chaff doesn't usually entail high cost to employ compared with other ECM techniques. When comparing chaff with the DECM techniques against monopulse tracking radar, chaff provides a very cost effective ECM. Sequential lobing tracking techniques are more susceptible to angle DECM. However, the angle jamming of tracking radar utilizing monopulse is more difficult due to the characteristics of the monopulse

beam pattern. The DECM receiver can sense only one steady beam and there is no AM modulation in the transmitting beam of monopulse radars when tracking. Therefore the DECM receiver provides no information for directing the DECM jammer when to turn on and off. Sometimes the DECM may accentuate the jamming aircraft position to the victim radars. DECM angle deception, from a single source, against monopulse is not as effective as two source jamming [Ref. 18: pp.398-399].

On the other hand, chaff creates a wide spread echo signal and the reaction of monopulse tracking radar is similar to any other tracking radars. Monopulse trackers will track the strongest echo signal, which may be produced by chaff. Chaff can eventually defeat a monopulse tracking radar with proper deployments.

2. Radar Absorbing Material

In order to use RAM on the aircraft, the weight and cost factors must be considered. The thickness of RAM depends on the frequency. The effect of attenuation per unit depth in absorbing material will be increased, as frequency is increased. Therefore the thickness of absorber can be decreased as frequency is increased. RAM coatings are not very practical at low frequencies. However, recent trends for the radar systems shows that the frequency band gradually increases up to the millimeter region. Therefore the use of RAM may become more prominent.

It will probably be attended by high cost because of the newness and complexity of the technique.

3. Stealth

In fact, even though sophisticated stealth techniques are employed, one cannot completely eradicate reflections to a receiving antenna. Accordingly, SAM acquisition and tracking radar can detect skin echoes to some extent, depending on the target range and the remaining RCS. The effectiveness of the stealth fighter against the SAM is based on the fact that SAM radars have to acquire normal-sized targets just before the target aircraft reaches SAM's lethal range, and SAM has a minimum range because the missile has a required launch

and acceleration time to properly track the target. In the case of the stealth fighter, SAM radar picks up the target at considerably shorter range due to its RCS reduction. The attacker may therefore be located inside the minimum firing range [Ref. 12: p.66].

D. DECOYS

1. Expendable Jammer

The use of EJs against a radar missile system can confuse enemy radar operators. Frequently EJs are mistaken for airborne targets. Thus, they may attempt to shoot down EJs with expensive missiles.

2. Remotely Piloted Vehicle

The primary advantage of the RPV is use in a high threat environment without loss of personnel and expensive aircraft. RPVs are more difficult to detect and shoot down than manned aircraft due to their small size. Even though RPVs are small, RCS enhancement can be used to confuse or deceive enemy radar.

E. DESTRUCTIVE COUNTERMEASURES

1. Anti-Radiation Missile

ARM directly attacks radars by homing on the radar radiation. ARM missiles can be installed on any type of aircraft for the purpose of self protection against SAM radars. A trade off is necessary since ARMs utilize weapon stations on the aircraft thereby reducing the loadout of other primary weapons.

Therefore ARM is usually delivered by specific aircraft which carry out suppression of enemy air defense (SEAD) as, for example the Wild Weasel. The effectiveness of ARM against SAM radars was fully proved during the Vietnam war and Iran/Iraq war. Several countries have developed and produced ARM. For example, Shrike, high-speed anti-radiation missile (HARM) and sidearm by the US; Armat, supersonic tactical anti-radiation (STAR) missile by France and air launched anti-radiation missile (ALARM) by England.

The use of ARM for destroying SAM systems will probably increase because of their standoff capability and reduced threat against own aircraft.

2. Wild Weasel Tactics

For the performance of a successful mission, Wild Weasel uses low level navigation tactics. Low level flight will not only make detection hard, but also the SAM threat is decreased due to the higher ground clutter. This allows Wild Weasel an increased element of surprise against SAM sites. The combination of recently developed ARM, which provides a longer range and more flexible launch capability, and Wild Weasel tactics can contribute to greatly improved suppression of enemy SAM activities.

V. CONCLUSION

It is difficult to effectively jam radars with one technique only. Individual techniques cannot successfully achieve monopulse radar jamming. It may be impossible to jam the radar completely even under the multiple techniques condition. Each ECM technique is tailored for only a specific portion of the radar to provide a partial jamming effect. Therefore, several ECM techniques should be integrated with each other in order to completely jam the entire radar systems. It is thus desirable to employ the various ECM techniques as simultaneously as possible to enhance the overall jamming effect.

As illustrated in chapter four, some ECM techniques against monopulse radars are very impractical. Cross-polarization jamming and cross-eye jamming are also not good techniques for application to monopulse radars due to the requirements of very high SNR. Image jamming is also not a dependable jamming technique without special knowledge of the victim radar. However, the other techniques that have been covered have a good effect on degradation of monopulse radar performance when combined with one another.

Five different categories of ECM techniques against monopulse radar; denial jamming, deception jamming, passive countermeasures, decoys, and destructive countermeasures; should be well integrated to give the best result in jamming effectiveness. Denial jamming techniques have excellent jamming effects. Denial jamming can be employed by attacking aircraft, but it is usually achieved through standoff jamming aircraft. In deception jamming, the three jamming techniques which are; range, velocity, and angle deception; should be integrated in the one repeater system, as shown in Figure 26. With passive countermeasures, chaff is very cost effective. Most attack/fighter aircraft have self protection chaff dispensing capability. In addition, RAM and stealth techniques will certainly impact on the future radar jamming field. In decoy methods, the use of cheap expendable drones or RPV will greatly increase the survivability of the future

strike aircraft. When considering probability of kill, the survivability of aircraft is theoretically proportional to the number of targets including false targets created by decoys. Destructive countermeasures can usually be performed by specially dedicated aircraft equipped with special weapons, ARMs, which can detect and attack the position of radar radiation sources. The employment of ARMs or Wild Weasel aircraft is a top growth area, projected well into the next century.

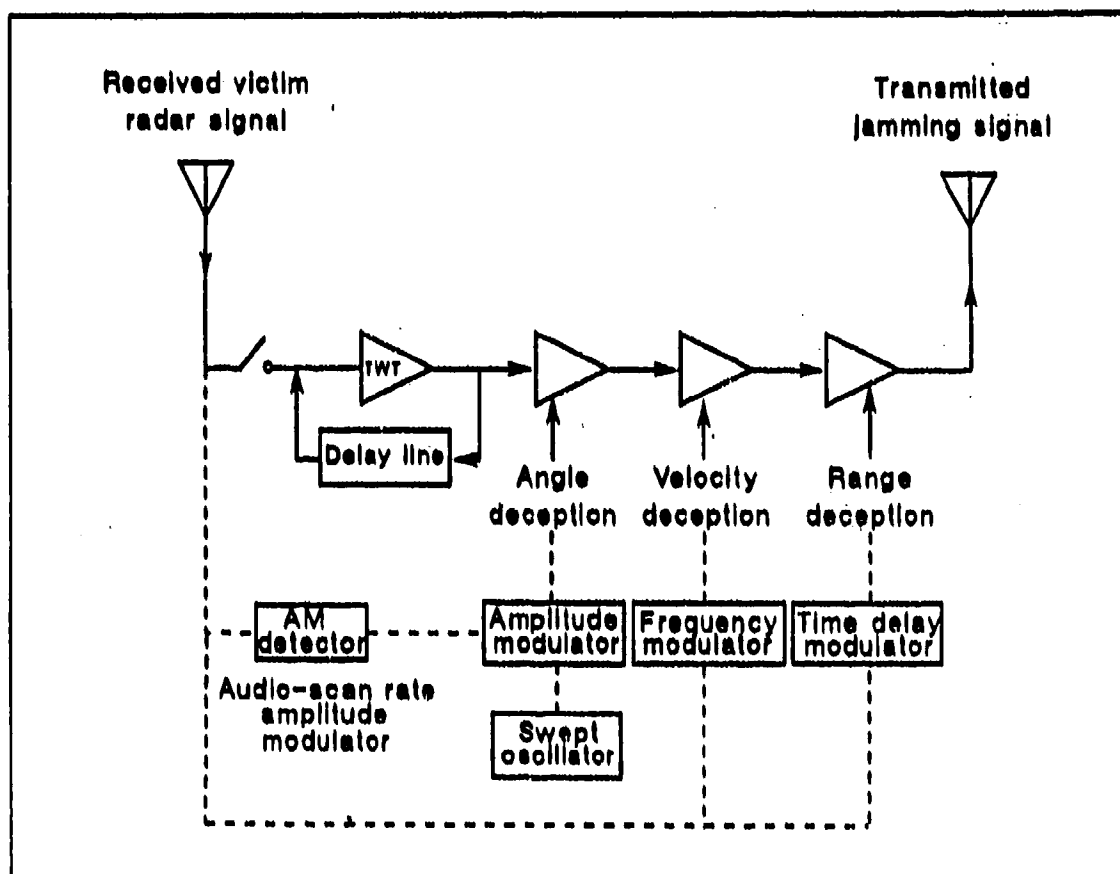


Figure 26. Block diagram of integrated deception jammer.

In conclusion, these techniques should be properly integrated to optimize ECM techniques while conserving resources against monopulse radars. The following combinations are recommended as a best approach for a strike force package.

Attacking aircraft need to be equipped with both passive countermeasures and integrated deception jammer. Denial jamming is performed by the standoff jamming aircraft, which require relatively high output power. Expendable jammers such as decoys can be carried on any of these aircraft to additionally confuse the enemy radar operators or system. In relation with these ECM techniques, evasive maneuvers have to be included to complement the jamming effectiveness. Finally, Wild Weasel type aircraft with ARM take part by destroying forward or high threat radar systems.

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